AGARD-AR-333

AGARD

ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT
7 RUE ANCELLE, 92200 NEUILLY-SUR-SEINE, FRANCE

AGARD ADVISORY REPORT 333

Piloted Simulation in Low Altitude, High Speed Mission Training and Rehearsal

(la Simulation pilotée pour l'entraînement et la préparation des missions à basse altitude et à grande vitesse)

This Advisory Report was prepared at the request of the AGARD Flight Vehicle Integration Panel.

NORTH ATLANTIC TREATY ORGANIZATION

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North Atlantic Treaty Organization
Organisation du Traité de l'Atlantique Nord

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Piloted Simulation in Low Altitude, High Speed Mission Training and Rehearsal

(AGARD-AR-333)

Executive Summary

The subject of low altitude flying training has received increased attention in recent years for political and technical reasons, including cost, environmental impact and the expanding training requirements of modern airborne weapon systems. Conducting low-level flying training 'live' is becoming less and less acceptable in many NATO nations, while the threat continues to demand even lower altitudes at higher speeds. Restrictions on low flying training exist in many countries, and include reduced low flying time, speed restrictions, and altitudes restricted to no lower than 1000 ft.

Following the AASC studies on "Low Level Flight Training" (AGARD-AR-288) and "Reduction of the Environmental Impact of Operational Flying Training" (AGARD-AR-295), Working Group 20 was established by the AGARD Flight Mechanics Panel (now the Flight Vehicle Integration Panel) to build on their conclusions and to examine the current capability and future potential of simulation technology in low altitude high speed mission training and rehearsal. It held its first meeting in October 1991. In conducting its review, the Working Group examined some relevant mission simulators in several NATO countries: the UK Harrier GR Mk5/7 mission simulator, the German Tornado Low-Level Test Bed simulator, and the US Apache helicopter Combat Mission Simulator. This report is based on the collective wisdom and experience of the Working Group members, and on the lessons learned from visits to these simulators. Working Group members were drawn from 6 Nations: Canada, Germany, Italy, Netherlands, UK and USA; and represented the simulation industry, the aircraft industry, research organisations and users, including three pilots with appropriate operational experience.

The report contains much general information about mission tasks, mission simulation, and simulation technology, which will be of interest to many people involved in the acquisition and exploitation of piloted flight simulators. The content is deliberately not limited merely to the specific cueing issues of simulating high speed flight close to the ground. The report deals primarily with fast jet aircraft, but many technical factors are common to rotary wing vehicles.

Key conclusions include:

- training simulators and the aircraft must be viewed as complementary components in the total training package;
- full mission simulation is a complex task, and low altitude flight is the most difficult phase of fast-jet operations to simulate in terms of the cues needed by the pilot;
- simulation of the outside world visual scene, both visually and to represent sensors, is the critical technology;
- there are important procurement issues which need to be addressed, particularly concerned with the provision of aircraft and systems data, and with decisions on the visual system to be employed.

Recommendations are made for further research in many areas, including:

- visual scene generation and scene content;
- visual scene display technology;
- requirements and standards for scene database preparation;
- natural environment models;
- data package requirements and standards for aircraft and systems performance;
- scenario generation methods and tools, the modelling of 'intelligent' forces, and data standards;
- facilities for the instructor and for mission management;
- motion cueing;
- application of distributed simulation technology.

Despite the substantial sums of money invested in buying military training simulators, and the increasingly key role that simulators play in achieving operational readiness and effectiveness, research on piloted flight simulation technology and training effectiveness is neither well-funded nor widespread. There is a continuing role for AGARD to stimulate and coordinate research in these areas. This report has identified several items which might form the subject for future AGARD Working Groups.

La simulation pilotée pour l'entraînement et la préparation des missions à basse altitude et à grande vitesse

(AGARD AR-333)

Synthèse

Pour des motifs techniques et politiques, le sujet de l'entraînement au vol à basse altitude suscite de plus en plus d'intérêt depuis quelques années. Parmi ces motifs figurent les exigences croissantes en matière d'entraînement, le coût et l'impact sur l'environnement des systèmes d'armes aéroportés modernes. La conduite, en situation réelle, de l'entraînement au vol à basse altitude est de moins en moins acceptable pour bon nombre des pays membres de l'OTAN, tandis que l'évolution de la menace nécessite de voler plus bas et plus vite. Dans nombre de pays, l'entraînement au vol à basse altitude est sujet à des restrictions telles que la limitation des heures de vol, la limitation des vitesses et l'imposition d'un plafond de 1,000 pieds.

Suite aux études réalisées par l'AASC sur l'entraînement au vol à basse altitude (AGARD-AR-288) et sur l'atténuation de l'impact sur l'environnement de l'entraînement au vol opérationnel (AGARD-AR-295), le groupe de travail No. 20 a été créé par le Panel AGARD de la mécanique du vol (l'actuel Panel conception intégrée des véhicules aérospatiaux), afin de poursuivre plus en avant leurs conclusions et d'examiner les possibilités actuelles et futures des technologies de simulation pour l'entraînement et la préparation des missions à basse altitude et à grande vitesse. Le groupe s'est réuni pour la première fois au mois d'octobre 1991. Lors de son examen, le groupe a étudié un certain nombre de simulateurs de mission utilisés dans différents pays de l'OTAN: le simulateur de mission de l'UK Harrier GR Mk5/7, le simulateur/banc d'essai basse altitude allemand du Tornado et le simulateur de mission de l'hélicoptère américain Apache. Ce rapport est basé sur les connaissances et l'expérience des membres du groupe de travail, ainsi que sur les enseignements tirés des visites de simulateur effectuées. Les membres du groupe de travail ont été fournis par six pays: le Canada, l'Allemagne, l'Italie, les Pays-Bas, la Grande-Bretagne et les Etats-Unis, représentant l'industrie des simulateurs, l'industrie aéronautique, les organisations de recherche et les utilisateurs, y compris trois pilotes ayant de l'expérience opérationnelle appropriée.

Le rapport, qui contient beaucoup d'informations d'ordre général sur les tâches opérationnelles, la simulation de la mission et les technologies de la simulation, intéressera tous ceux qui sont concernés par l'acquisition et l'exploitation des simulateurs de vol pilotés. Il s'affranchit volontairement des limites de la simulation du vol à grande vitesse près du sol. Il traite principalement des avions à réaction à grande vitesse, mais dans beaucoup de cas les facteurs techniques en question sont communs aux aéronefs à voilure tournante.

Les principales conclusions sont les suivantes :

- les simulateurs d'entraînement et les aéronefs doivent être considérés comme des éléments complémentaires du programme global d'entraînement;
- la simulation complète de la mission est une tâche complexe dont le vol à basse altitude représente la phase des opérations d'un avion de combat à grande vitesse la plus difficile à simuler du point de vue des stimulations à transmettre au pilote;
- les technologies déterminantes sont celles qui permettent la simulation de la visualisation du monde extérieur;
- des questions importantes sont à résoudre concernant les achats de matériel, en particulier en ce qui concerne la fourniture de données avion et systèmes et les décisions qui seraient à prendre vis-à-vis des systèmes de visualisation à adopter.

Des recommandations sont faites concernant de futurs travaux de recherche dans de nombreux domaines y compris:

- la génération de la scène visuelle et du contenu de la scène;
- les technologies de visualisation de la scène visuelle;
- les spécifications et les normes relatives à l'établissement des bases de données de la scène visuelle;
- la modélisation du milieu environnant;
- les spécifications et les normes relatives aux progiciels de simulation des performances des aéronefs et des systèmes;
- les outils et les méthodes de génération de scénarios, la modélisation des forces "intelligentes", et les normes de données;
- les moyens mis à la disposition des instructeurs et les moyens de gestion de la mission;
- la simulation motrice;
- la mise en œuvre des technologies de simulation réparties.

Malgré les sommes considérables qui ont été investies dans les simulateurs d'entraînement militaires, et en dépit du fait que les simulateurs jouent un rôle de plus en plus important en ce qui concerne l'état de préparation opérationnelle et l'efficacité des missions, la recherche en technologies de simulation du vol piloté et les travaux sur l'efficacité de l'entraînement ne sont ni très répandus, ni très bien financés. L'AGARD doit, par conséquent, continuer de coordonner et de stimuler les travaux de recherche dans ces domaines. Ce rapport identifie un certain nombre de sujets susceptibles de faire l'objet de futures études de l'AGARD.

Contents

Note also that each chapter contains its own detailed contents list, to serve as a form of index.

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Glossary

2-D	two-dimensional
3-D	three-dimensional
AAA	Anti Aircraft Artillery
AAR	Air to Air Refuelling
ACM	Air Combat Manoeuvring
ACMI	Air Combat Manoeuvring Instrumentation
AEW	Airborne Early Warning
agl	above ground level
AI	Air Intercept
AI	Air Interdiction
ALARM	Air Launched Anti-Radiation Missile
AOI	Area Of Interest
ARI	Army Research Institute (US Army)
ARINC	Aeronautical Radio Inc.
ASIC	Application Specific Integrated Circuit
ASTAs	Aircrew Synthetic Training Aids
ASW	Anti Submarine Warfare
ATO	Air Tasking Order
AWACS	Airborne Warning and Control System
BAI	Battlefield Air Interdiction
BFS	Basic Flight Simulator
BVR	Beyond Visual Range
C2	Command and Control
C3	Command, Control and Communications
CAA	Civil Aviation Authority
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CAP	Combat Air Patrol
CAS	Close Air Support
CAT	Computer Aided Training
CAW	Combined Arms Warfare
CBT	Computer-Based Training
CCTT	Close Combat Tactical Trainer
CGI	Computer Generated Image
CPT	Cockpit Procedures Trainer
CRM	Crew Resource Management
CR	Combat Ready
CRT	Cathode Ray Tube
CT	Continuation Training
DBWS	Database Workstation
DCA	Defensive Counter Air
DFAD	Digital Feature Analysis Data
DIS	Distributed Interactive Simulation
DLMS	Digital Land Mass System
DMA	Defense Mapping Agency
DOB	Dispersed Operating Base

DOD	Department Of Defense
DRA	Defence Research Agency
DRLMS	Digital Radar Land Mass Simulator
DTED	Digital Terrain Elevation Data
ECM	Electronic Counter Measures
ESIG	Evans and Sutherland Image Generator
ESM	Electronic Support Measures
ESPRIT	Eye Slaved Projected Raster Inset Technology
EUCLID	European Cooperation for the Long Term in Defence
EW	Electronic Warfare
FAA	Federal Aviation Administration
FLIR	Forward Looking Infra-Red
FLOT	Forward Line Own Troops
FMS	Full Mission Simulator
FOHMD	Fibre Optic Helmet Mounted Display
FOV	Field Of View
FSDR	Flight Simulator Development Rig
FVP	Flight Vehicle Integration Panel
GCI	Ground Controlled Intercept
GMR	Ground Mapping Radar
GPS	Global Positioning System
GTDB	Generic Transformed Data Base
HARM	High Speed Anti-Radiation Missile
HDI	High Detail Input/Output (as in SIF/HDI)
HDTV	High Definition Television
HIMEZ	High Level Missile Engagement Zone
HRL	Human Resources Laboratory
HUD	Head Up Display
IEEE	Institute of Electronic and Electrical Engineers
IFF	Identification Friend or Foe
IG	Image Generator
IIS	Infra-red Imaging System
IOS	Instructor Operator Station
IP	Initial Point
IPS	Interactive Pilot Station
IQTG	International Qualification Test Guide
IR	Infra-Red
ITEMS	Interactive Tactical Environment Management System
JTIDS	Joint Tactical Information Distribution System
km	kilometre
LCD	Liquid Crystal Display
LCR	Limited Combat Ready
LLTB	Low Level Test Bed
LLTV	Low Light Television
LOD	Level of Detail
MIL STD	Military Standard
MODDIG	Modular Digital Image Generator
MOS	Minimum Operating Strip
msd	minimum separation distance

MTF	Modulation Transfer Function
NAO	UK National Audit Office
NATO	North Atlantic Treaty Organisation
NAWC-TSD	Naval Air Warfare Center, Training Systems Division
NBC	Nuclear, Biological, Chemical
NLR	Nationaal Lucht- en Ruimtevaartlaboratorium (National Aerospace Laboratory)
nm	nautical mile
NVG	Night Vision Goggles
OCA	Offensive Counter Air
OCU	Operational Conversion Unit
OE	Operational Equipment
OFTS	Operational Flight and Tactics Simulator
OLF	Operational Low Flying
OPSEC	Operational Security
PIO	Pilot Induced Oscillation
PTT	Part Task Trainer
RAes	Royal Aeronautical Society
RAF	Royal Air Force
RDF	Remote Debriefing Facility
RGB	Red-Green-Blue
RISC	Reduced Instruction Set Computers
RV	Rendezvous
RWR	Radar Warning Receiver
SAM	Surface to air missile
SAR	Synthetic Aperture Radar
SDBF	Simulator Data Base Facility
SEAD	Suppression of Enemy Air Defences
SHORADEZ	Short Range Air Defence Engagement Zone
SIF	Standard Simulator Data Base (SSDB) Interchange Format
SSDB	Standard Simulator Data Base
STE	Synthetic Training Equipment
STRATA	Simulator Training Research Advanced Testbed for Aviation
TACRECCE	Tactical Air Reconnaissance
TDP	Technical Demonstrator Programme
TER	Training Effectiveness Ratio
TFOV	Total Field of View
TFR	Terrain Following Radar
TRN	Terrain Reference Navigation
TTW	Transition to War
TV	Television
TWS	Track While Scan
USAF	United States Air Force
VLSI	Very Large Scale Integration
VSTOL	Vertical Short TakeOff and Landing
VTS	Versuchsträger Tornado Simulator
WGS84	World Geodetic System 1984
WSO	Weapons System Officer
WVR	Within Visual Range

CHAPTER 1

INTRODUCTION

CONTENTS

1 BACKGROUND

1.1 Aims

The subject of low altitude flying training has been receiving increasing attention in recent years for a number of reasons, both political and technical. These include cost, environmental impact and the expanding training requirements of modern airborne weapon systems. Conducting low-level flying training 'live' is becoming less and less acceptable in many NATO nations. As a result, there is strong interest in the current and potential capability of flight simulators for such training.

Effective piloted simulation of low altitude, high speed flight missions poses significant challenges to current and evolving technology but would have major operational and political benefits. This report, the result of studies by a Working Group sponsored by the Flight Mechanics Panel (which has now evolved into the Flight Vehicle Integration Panel, FVP), reviews the current capability of piloted simulation in low altitude, high speed mission training and rehearsal, and what improvements are in prospect. It concentrates on simulation technology, as a contribution to decisions on training requirements and equipment specification.

The aims of the Working Group were

1. To provide a clear statement on the current capability of, and the anticipated potential for, piloted flight simulation in low altitude high speed mission training and rehearsal.
2. To identify in low altitude military mission activities:
   a. those tasks which require simulation because they cannot effectively be carried out in real aircraft for operational or political reasons;
   b. those tasks where simulation offers a positive supplement to real flight;
   c. and those tasks which are best carried out in real flight.
3. To identify those aspects of mission simulation which are required, and are considered technically feasible, but are currently represented unsatisfactorily. This will provide clear guidance on the priorities for simulation technology research to tackle outstanding problems.
4. To provide guidance to procurement organisations on the improvements in simulation technology likely to be available in the next 5-10 years which will increase the capability to carry out mission training and rehearsal in flight simulators.
5. To collate and review feedback from the current generation of mission simulators.
6. To recommend priorities for future research on simulation technology taking into account current research activities.

As part of its work, the Working Group has tried in this report to answer the following questions:

1. where does today's simulation technology fall short in providing what is needed?
2. what are the technological obstacles to achieving what is needed?
3. what kinds of programmes might overcome the technical obstacles?
4. what level of costs might be expected?

Dimensions of the problem are not just technical, but also embrace issues of training policy. This report concentrates on simulation technology and the technical issues. It deals primarily with fast jet aircraft but many factors are common to rotary wing vehicles.

The topic of the report is simulation, not just simulators. A simulator is a device, or training medium, while simulation is the application of the device to a training task. It is important that this distinction is recognised.

Fidelity of simulation is clearly important, but is a difficult topic to define and measure. Among the issues which fall under the heading of 'fidelity' are the physical form of the simulator, the accuracy of the mathematical models employed in the device, and the perceptual agreement between the modelled role of the simulator and its real-world role. Broader simulation issues are concerned with the way the device is operated, the method used to provide instruction and the motivation of both the students and the instructors.

1.2 Activities and membership

In conducting its review, the Working Group examined some relevant mission simulators which were in service, or about to come into service, in several NATO countries, and has attempted to bring together the lessons learned from them. These simulators were the UK Harrier GR Mk 5/7 mission simulator, the German Tornado Low Level Test Bed simulator, and the US Apache helicopter Combat Mission Simulator. The German Tornado Low Level Test Bed simulator (or VTS - Versuchstraeger Tornado Simulator) was particularly valuable, as it specifically studied the needs of low altitude simulation.

This report is based on the collective wisdom and experience of the Working Group members, on the lessons learned from visits to the simulators referred to above, and on evaluation of the experimental results from the German Tornado Low Level Test Bed Simulator.

The Working Group held six working meetings between Oct 91 and Mar 94:

Oct 91 Defence Research Agency, Bedford, UK
Feb 92 CAE Stolberg, Germany
May 92 Fort Rucker, Alabama, USA
Feb 93 RAF Wittering and DRA Bedford, UK
May 93 Alenia, Turin, Italy
Mar 94 NLR, Amsterdam, Netherlands

Working Group members were drawn from 6 Nations: Canada, Germany, Italy, Netherlands, UK and USA; and represented the simulation industry, the aircraft industry, research organisations and users, including three pilots with appropriate operational experience.

1.3 Training regimes

Low altitude, high speed mission training and rehearsal is the most demanding simulated combat operation possible in peace-time, and is the culmination of several years of pilot training. The relevance of simulation to training for this role has to be considered as part of the whole training regime.

Training is initially concerned with learning and skill acquisition, then with skill maintenance, assessment and possibly pre-mission practice, all to achieve safe and effective operation of the aircraft and its systems in its operational role.

In a typical training regime, low altitude flying training is introduced briefly (Defence, 1990 - *NB References are given in the form (Defence, 1990) and are listed in full in the References section at the end of the Report.*) during basic flying training (eg in the UK, using the Tucano aircraft), and then undertaken as a major task by fast jet crews during Advanced Flying Training (eg using the Hawk aircraft in the UK). Crews are assumed to arrive at a fast jet Operational Conversion Unit (OCU) attuned to the intensive demands of learning to fly and fight in a modern combat aircraft. Low altitude flying is clearly a significant component during operational conversion to any aircraft type (eg Tornado) for which low flying is part of the operational role. Following tactical flying training, pilots carry out further training in a front line squadron. From recruitment to being declared 'combat ready' can take a pilot up to 4 years (Defence, 1990).

Synthetic training equipment used in aircrew training can comprise a wide range of devices, from desk top and part-task systems trainers, via basic flight simulators to full mission simulators (AGARD, 1992 page 95), all of which complement live flying. This range is discussed elsewhere in this report (see Chapter 2 Annex A).

1.4 Some definitions

To enable this report to review the subject of piloted simulation in low altitude, high speed mission training and rehearsal, there is a need for some key definitions.

- what is low altitude?
- what is high speed?
- what is mission simulation?
- what is mission training and rehearsal?

Low Altitude. Fast jets are defined to be flying low ("low level") when they are less than 2000 ft above ground level. This is the UK definition (Defence, 1990). Other countries may differ slightly. (Helicopters, however, are defined to be low flying when they are less than 500 ft above ground level.) Military jets are normally permitted to fly lower than 2000 ft in peace-time, for example, down to 250 ft in the UK and even lower in certain specified areas, but some countries are more restrictive and decree a minimum height of 1000 ft. When flying low, the definition is more strictly given in terms of 'minimum separation distance' (msd), i.e the clearance distance in all directions. Most low flying training takes place between 250 and 600 ft msd. Operationally, low flying will generally be below 250 ft and down to 100 ft or even lower. The phrases "low level" and "low altitude" are used interchangeably in this report.

High speed. High speed in war-time might be 600 knots or more (Defence, 1990) but in peace-time it is more typically 450 knots, or at most 550 knots.

Operating at high speed close to the ground is a skilled flying task. For the pilot to be able to perform this task in a simulator, with the same level of attention and workload as would be used in real flight, demands effective visual and motion cues and accurate reproduction of the aircraft's handling qualities. If the cues and the simulated handling qualities are deficient, the pilot may still be able to perform the task, but at the expense of reduced critical attention to the rest of the mission tasks.

Mission simulation. Mission simulation requires simulation of the aircraft, its weapons and systems within an external environment appropriate to the mission. The mission elements that need to be included are outlined in detail later, in Chapter 2. The external environment includes the appropriate natural environment associated with the geographic and atmospheric conditions and an operational environment with suitable numbers, composition, location and behaviour of cooperating, friendly and opposing forces in the air and on the ground. Woodfield (1993) identified four primary environments: the internal vehicle environment (the cockpit and the crew interfaces), the external natural environment (including external visual scenes, and motion cues), cooperating force and threat environments and the command and control environment. The full set of environments is needed for mission simulation, whereas only the internal vehicle and external natural environments may be needed for training flying skills and only the internal vehicle environment for many procedural training activities.

Mission training and rehearsal. Mission training and mission rehearsal apply mission simulation to specific roles. In mission training, the pilot (or aircrew) will fly sorties over characteristic terrain of the type likely to be encountered in an operational mission, to practise a cross section of the skills and techniques applicable to the aircraft type and its role, in representative conditions. In mission rehearsal, a specific mission operation to a designated target is practised, with a specific weapon fit. It will use carefully identified routes over a simulated version of the terrain to be encountered on the real mission (provided data is available), with realistic time and distance constraints, and in the expected threat environment. Mission rehearsal is more 'practice' than 'training' and allows the crew to consider alternative courses of action and to experience possible changing circumstances during the mission. The major mission components - brief, perform, debrief - are as close to real operations as possible. Debrief of a simulated sortie potentially has the added benefit of a full play-back of what happened.

A more extended discussion of mission simulation is given later in this Chapter (section 1.7), the operational needs are outlined in chapter 2 and the nature of a typical mission simulator is outlined in Chapter 3.

Environmental considerations in peacetime have led to increasing restrictions being placed on low flying training in many countries. Such limitations include reduction in the amount of low flying time, speed restrictions, increase of minimum altitudes, reduced number of low flying areas and reduction in night flying hours. Flying training may be restricted to no lower than 1000 ft even though 250 ft at 420 knots is widely recognised as the "best compromise between training value and environmental impact" (see AGARD, 1992, page 71). "The training areas that are available (eg for the 'Flag' exercises and at Goose Bay etc) are scarcely sufficient to meet current demands" for low flying training (AGARD, 1992, page 77). There is also a need for specialised ranges for weapons, air combat and Electronic Warfare (EW) training yet the pressure to close such facilities is increasing (AGARD, 1992, page 77). Furthermore, the cost of deployment to 'Flag' exercises and remote special ranges is very high.

A requirement for the rehearsal of combat mission profiles in simulators exists partly as a result of these environmental pressures and also because many training tasks are difficult or impossible to perform 'live'. Among the training tasks where simulation has real (potential) value, because they are difficult to do live, are night flying operations, weapon firing, electronic warfare (EW), and operation in a comprehensive threat environment. Peacetime training flights cannot be flown under realistic combat conditions due to the absence of appropriate threats, the lack of friendly force participation, and the inability to represent other environments (NBC: Nuclear, Biological, Chemical; and ECM: Electronic Counter Measures), and clearly cannot be flown over the assumed combat areas. The 'live' training closest to real operations available in peacetime is participation in the USAF 'Flag' exercises, but even these have limitations. Simulation can provide other benefits, namely safe conditions in which to refresh highly reactive piloting skills, such as close air combat; no intrusion into the environment; and no disturbance to the general population.

In addition to addressing these problems, mission rehearsal in simulators should improve a crew's chances of survival on an actual mission by:

- allowing repeated runs at the target using different approaches at different heights and speeds to familiarise the crew fully with the most critical phase of the mission.

- viewing target defences and hostile radar coverage to provide an assessment of individual aircraft and composite formation vulnerability, then making adjustments as necessary.

- exploring multiple attack options to decide on the optimum solutions for force and package coordination.

Flight simulators have the potential to make these contributions to mission training. This report will review what has been achieved so far, identify what is important but is currently deficient in simulators, and summarise what prospects there are for improvement from existing technology and from further research.

1.5 Structure of the report

While the specific subject of this report is the simulation of low altitude, high speed flight, limiting the content merely to the specific cueing issues of simulating high speed flight close to the ground was deemed by the Working Group to be too narrow. The report therefore also considers the wider issues of mission simulation and contains much general information about mission tasks, mission simulation and simulation technology (particularly in chapters 4 and 5) which it is hoped will be of interest to many people involved in the acquisition and use of flight simulators.

Chapter 2 defines, in a comprehensive way, the nature of operational missions, and the constituent mission task elements (not just low altitude, high speed flight), in order to define the operational need. It then translates the operational needs into general simulation requirements and elaborates the context, that is the support facilities and functions, in which a simulator needs to operate to be an effective training system. The chapter also includes an Annex on Training Philosophy and an introduction to Synthetic Training Equipment and the benefits of using such equipment. An important conclusion of this chapter is that it shows that a complete mission contains much more than the low altitude, high speed task.

Chapter 3 outlines the components of a typical mission simulator, to provide background information for later chapters which review the capabilities of simulation technology in more detail. It emphasises that a mission simulator must supplement the aircraft simulation that the pilot flies with an appropriate operational scenario, or context. This adds considerably to the complexity. The chapter also describes briefly the relevant technical features of the two specific mission simulators which have served as sources of information and experience for this report: the German Air Force Tornado Low Level Test Bed (or VTS - Versuchstraeger Tornado Simulator) and the Harrier GR Mk 5/7 Mission Simulator at RAF Wittering in the UK.

Chapter 4 discusses the pilot cueing environment in terms of the internal cueing environment (including the cockpit), the visual cueing environment, including the display requirements and the motion cueing environment. In reviewing visual display technology in some detail, the chapter assesses the advantages and disadvantages of the possible display solutions and concludes that an "area of interest" system is currently the most appropriate technology for a fast jet aircraft simulator. The chapter also reviews motion cueing devices and the role and value of motion cues.

Chapter 5 examines the various models and supporting data required: for the aircraft being simulated, for the external world and for the scenario. It discusses the

key performance parameters of image generators, and identifies and analyses the databases needed in a mission simulator. These include visual and sensor-based scene databases, own aircraft performance databases, and battle environment and scenario databases. Issues of database correlation are also discussed. The interconnection of mission simulators by electronic communication networks is not a major part of this study, although it is considered briefly in this chapter.

Chapter 6 discusses some human factors topics associated with the use of simulation for low altitude, high speed mission training.

Chapter 7 reviews how integrated mission systems should be represented in simulators and discusses some of the arguments for simulation, stimulation or emulation of mission computers and other black boxes.

Chapter 8 presents the main overall conclusions. In general, each chapter also contains its own conclusions and recommendations.

Chapter 9 summarises the recommendations including further research and other work required.

Throughout the body of report, an attempt is made to summarise what is needed, what can be achieved today, what could be done (via appropriate research and development), where specific emphasis is required to meet the needs, what is likely or unlikely in the next 10-15 years, and what the inadequacies mean in terms of not being able to train in a simulator.

Furthermore, each chapter contains its own detailed contents list, to serve as a form of index.

1.6 Related studies and other background papers

Several papers of major relevance appeared before and during the life-time of the Working Group. These are reviewed briefly here.

As a result of an initiative by the AGARD National Delegates Board, the Aerospace Applications Studies Committee sponsored a workshop in October 1989 to examine "Low Level Flight Training", with particular reference to simulation. The workshop report (AGARD, 1990) concluded that it "could offer no recommendation for reducing the present levels of fast-jet low flying" and that "improvements in the total training concept were necessary, to include both live flying and synthetic training". Among its additional conclusions, the workshop "supported the use of facilities (such as the German Tornado test bed and the UK Harrier mission simulator) that would provide additional information on meeting operational training requirements for low level flying". This recommendation led directly to the formation of the Working Group which has produced this report.

In 1990 the UK National Audit Office examined (NAO, 1990) the need for low flying training, the arrangements for its control and the consideration given by the UK Ministry of Defence to alternatives to the present arrangements. It identified some of the constraints that led to training flights being "restricted to speeds significantly slower than would be required in war" and to only a "very small proportion of low flying in the United Kingdom being at the operational height of 100 feet". "Most low flying training is carried out at greater heights and lower speeds than those which would apply in war." Among its conclusions, the report recommends that the UK Ministry of Defence "should consider the scope for ... greater use of (simulators) to supplement the current training".

A comprehensive report (Defence, 1990) on "Low Flying", by the UK House of Commons Defence Committee, reviewed, during hearings in 1989, the position on low flying in the United Kingdom, the impact of low flying on the environment, safety and plans for the future. The review concentrated on fast jets, not helicopters, transport or maritime aircraft. The report pointed out that "low flying over familiar terrain has little training value", which suggests a role for simulators, and emphasises the importance of appropriate databases. It also identifies that "there will be an increasing need to train at night", to familiarise crews with flying using Night Vision Goggles (NVG's). The Working Group considers that improved simulators may be able to train some additional tasks so that, on balance, the impact on the environment is not increased. On costs, the Defence Committee estimated that the purchase cost (<u>not</u> replacement cost) of RAF aircraft lost in low flying accidents in 1988 was £80M. The committee also noted that, over the 5 years to 1990, UK MoD spent £125M on procurement of flight simulators and £11M on related R&D and recommended that the UK Government "substantially increase their commitment to R&D on simulation technology".

A mission simulator in operation in France for the Mirage 2000N aircraft is discussed in a paper "Visual System for Low Level Flight Training" (Rapp, 1990). This simulator is in a category comparable to the German Tornado test-bed and the UK Harrier mission

simulator. The paper concludes that "the visual system fulfils the requirements necessary to train the crew to fly and operate the Mirage 2000N in low-level flying and adverse weather and threat conditions". Despite this, the report still seeks enhancements to the visual system, in total field of view and scene resolution, more to improve target acquisition and designation, rather than for low-level flying as such.

An AGARD Symposium on "Piloted Simulation Effectiveness", sponsored by the Flight Mechanics Panel, was held in Brussels in October 1991 (AGARD, 1991). The keynote speech to the Symposium, on "Opportunities for flight simulation to improve operational effectiveness", given by Ministerialdirektor J Heyden from the German Federal Ministry of Defence, highlighted four outstanding questions:

- what are the minimum equipment requirements for both development simulation and training simulation?
- can simulator fidelity be improved by introducing new cost-effective enabling technologies?
- are there technical or training options available to increase pilot acceptance for low-level high-speed flight simulation?
- what actions should be taken to enhance standardization and implementation of full mission simulation facilities for common and complementary use within the NATO forces?

Among the technical papers presented at the symposium were two on recent mission simulators: Clifford (1992) described the Harrier GR Mk 5/7 Mission Simulator, which entered service in the UK in 1993; while Morris and van Hemel (1992) outlined the changes being considered for the German Tornado simulators. An extensive study was conducted by the German MoD during 1991/2 (van Hemel, 1992; Foldenauer, 1992; and Morris and van Hemel, 1992), in order to gather information about the visual system and motion system requirements to provide the fidelity needed for simulated low level flying training. This Tornado study (more details of which are given in chapter 3) is one of the key sources of information for this report.

A study published in 1992 (NAO, 1992) by the UK National Audit Office examined the acquisition, utilisation and effectiveness of simulators used in training. It defined simulation as "a means of producing a representation of operational conditions to enable trainees to acquire and practice skills, knowledge and attitudes", and a simulator as "any system or equipment used in the practice of simulation". The report's strongest recommendation is a need for improved methods to measure training effectiveness.

Following the workshop on "Low Level Flight Training" (AGARD, 1990) discussed earlier, a further major study was conducted under the auspices of the AGARD Aerospace Applications Studies Committee, this time on "Reduction of the Environmental Impact of Operational Flying Training, Particularly at Low Level". While the study included all aircrew operational training, one specific objective set out to "consider how modern simulation techniques could best be used to contribute to the training required for optimum operational readiness". The report (AGARD, 1992) concluded that, particularly as a result of "identified weaknesses in visual presentation systems, ... simulation has not matured to the extent that it can replace tactical low flying training". Despite such identified weaknesses, however, it also concluded that "of all the methods of reducing environmental impact that have been considered, simulation could provide the greatest scope for achieving a practical solution", although it "will never be able to totally replace the need for live flying".

1.7 An introductory discussion of mission rehearsal

1.7.1 Definition

There is, as yet, no widely agreed definition of the term mission rehearsal. The following section develops current thinking on the understanding and disciplines of mission rehearsal, drawing extensively on a paper by Wiggers et al (Wiggers, 1989).

Every operational mission, regardless of how large or small its scope, goes through a series of processes as it passes from formulation to implementation. These processes are a sequence of stages which start with planners, then commanders, then operators, and so on. Generally categorized, these process steps are:

a. Inception/High Level Tasking.

b. Force/Unit Selection and Brief.

c. Force/Unit Preparation and Coordination.

d. Execution.

e. Debrief.

Rehearsal is an integral part of Force/Unit Preparation and coordination. Because of today's complex interactive system/counter-system technology, the

increasing number of variables influencing the outcomes of tactical exercises, the need for coordinated team efforts, and the increasing difficulty in predicting their combined effects, rehearsal has become a critical item of preparation, and should probably stand alone in the generalized list. If mission rehearsal were a stand-alone process it could, and probably would, affect the preceding phases of mission preparation as well as the most important phase: execution. Not all missions require the same degree of rehearsal because the range of variables encountered differs from mission to mission.

In order to understand the concept of mission rehearsal, we must first define uncertainty and how it affects the mission. Uncertainty in warfare is defined as a situation or condition which is vague or not exactly described. It can be broken down further into three general categories:

a. Situational Uncertainty. Uncertainty which arises from known conditions which cannot be controlled but may be included in planning (eg. variance in weather conditions).

b. Probabilistic Uncertainty. Uncertainty which arises from known conditions which cannot be controlled but may be statistically predicted (such as the probability of kill of a missile).

c. Operational Uncertainty. Uncertainty which arises from unknown conditions which may be neither controlled nor predicted (eg. the intentions and actions of other human operators, including those of opposing forces).

In recent years, development of simulation training concepts by the industrial/user communities has resulted in the specification and design of systems which advertise "mission rehearsal" capabilities. While most of these concepts do not, in fact, allow for mission rehearsal, they do form an important component in the hierarchy of training leading toward successful execution of a mission.

Mission training concepts can be broken down into three categories:

a. Mission Preparation. Tactical planners and commanders developing and refining tasks required for tactical forces or crews to execute a specific mission.

b. Mission Preview. Tactical forces or crews conducting initial familiarization for a specific mission. This can be performed utilizing personal computers or similar equipment.

c. Combat Mission Training. Tactical forces or crews conducting training scenarios, to which some factors, including a moderate level of uncertainty, have been realistically applied with the intent of training for a particular type of mission.

Based on the foregoing, mission rehearsal could then be defined as follows:

> **Mission Rehearsal:** Tactical forces and crews conducting trial performances, in which all factors, including an appropriate level of uncertainty, have been realistically applied to a situation with the intent of preparing for a specific mission.

Overall, mission rehearsal provides the ability to analyze and adjust a mission plan based upon lessons learned during the rehearsal. If the specified performance and characteristics of the mission have been met during the rehearsal, the mission plan is acceptable. Mission rehearsal can provide an objective method of analysing the performance and characteristics of a mission only if the requirements driving mission rehearsal allow it.

1.7.2 Defining the requirement for mission rehearsal

Specifying a system capable of providing mission rehearsal necessitates defining a set of requirements to which the system must adhere. Mission rehearsal requires the following:

a. Forces/crews.

b. Realism.

c. A specific mission.

d. Tactics.

e. Uncertainty.

Each of these items defines a set of requirements which must be applied in order for a system or method of mission preparation to be considered "mission rehearsal".

Forces/crews. Normally, forces/crews utilized during a rehearsal will already be trained in the basic operations

of their assigned equipment. However, even experienced crews have difficulty initially integrating multiple tasks under high-stress workloads. Therefore, forces/crews will require the ability to work under high-stress conditions, and the mission rehearsal facility must subject the personnel to high stress situations. Furthermore, the forces and crews involved must represent a high proportion of all the participants.

Mission rehearsal provides stresses and workloads associated with performing specific missions in a realistic environment. It has been found (Grodsky, 1965) that the introduction of realistic workloads and stress factors is important in predicting crew reliability during mission execution. The use of simplified tasks, crews other than the actual crew, lack of appropriate temporal sequencing of tasks, and the lack of stress (both psychological and physiological) were found to place the reliability of data obtained from non-realistic rehearsal environments in doubt. Additionally, exposure to high-stress workloads during rehearsal has been found (Courtice, 1988) to reduce the level of stress and workloads during actual mission execution. It should also be noted that a partial overlap between team members provides (Kleinman, 1989) an overall reduction in team workload. Thus, mission rehearsal provides a valuable means of gauging crew reliability during the actual mission, and has the potential benefit of increasing crew reliability by reducing stress during actual mission execution.

Realism. Realism refers to the kinds, amount, and complexity of the information needed in performing a mission. A realistic simulated environment is important since differences in task information between the simulation and the real world may produce errors in planning or executing a mission. There are two primary ingredients of realism: appearance and behaviour. Appearance is what the simulated environment is sensed to be (eg what it looks like, and what it sounds like). Behaviour is how significant elements in the environment act and react. Both appearance and behaviour must be considered in developing a realistic environment.

Appearance is strongly associated with visual scenes. The real-world terrain provides important cues for forces/crews to perform missions. Historically, terrain has played an important role in the outcome of military actions. Accurate terrain portrayal and detail is paramount for any form of mission rehearsal.

Cues are also required for other senses (such as kinaesthetic, aural, and tactile cues) when these cues affect the outcome of a mission. There is also a need to correlate the various sensors (such as radar, IR, laser, etc.) and out-of-the-window imagery to the extent that crews/forces can use and cross-check each source of information as it would be used and verified in real-world operations.

Behaviour, on the other hand, is usually associated with threats, although it also relates to terrain and weather. Threat behaviour is extremely important in practising and evaluating tactics for a specific mission. It is therefore necessary to model not only the physical characteristics of the threat, but also the underlying doctrine and force employment of the specific threat to be encountered during the actual mission. Threat systems must portray full capabilities within rehearsal. Special efforts should be put forward in threat portrayal. Partial or "close enough" portrayal should be avoided. It is also important to model friendly and neutral forces in a manner similar to the threat in order to provide a realistic, balanced conflict. Behaviour of terrain, weather and the interaction between the two must also be appropriately modelled.

A final consideration in realism deals with the fidelity of the simulated system(s). In order to practise a mission, all mission-critical equipment must be simulated and the simulated design must be concurrent with the system which will be used for the mission. The fidelity of the system must allow all performance limitations and characteristics necessary to perform the mission to be accurately recreated.

Required fidelity is a function of operational needs. What are considered as valid needs today may be inappropriate for the next potential conflict. The equipment to be used may not be configured in a manner which is today considered standard. Therefore, any devices developed or modified for mission rehearsal must have the ability to "add on" or be replaced economically and quickly. Fidelity for mission rehearsal is a question of providing the minimum task information needed to replicate those aspects of the appearance and the reactions of the equipment to be used. Rehearsing on devices with different operational formats, panels, controls, etc., may seriously detract from the overall effectiveness of the rehearsal. Clearly, added to this loss of realism is a possible loss in crew proficiency due to rehearsing on dissimilar controls.

Mission Rehearsal realism, therefore, imposes the following requirements:

a. Ability to grow or quickly adapt to operational needs.

b. Detailed real-world mission terrain with scene complexity, including cultural features, commensurate with the real world.

c. Correlation of all visual and sensor imagery.

d. System fidelity which allows all mission-critical functions to be performed.

e. System simulation matching actual deployed systems.

f. Threats, correct in appearance and behaviour, with doctrine specific to the threats which will be encountered during a specified mission.

g. Threat and friendly Command and Control (C2) and Command, Control and Communications (C3).

h. Balanced Red versus Blue versus other conflict simulation.

i. Realistic simulation of weather, terrain, and interaction between the two.

j. Simulation of seasonal and time of day changes.

1.7.3 A specific mission

Since mission rehearsal is a method of practising a specific mission, all aspects of the rehearsal must be compatible with the mission. Specifically, the tasking, preparation, briefing, execution, and debriefing should occur in the mission rehearsal in a manner consistent with the execution of the real mission. This also implies that some set of security requirements must be addressed for mission rehearsal, since operational security (OPSEC) is an integral part of mission planning.

Utilizing a specific mission imposes the following requirements:

a. Compatibility with existing and future mission planning and briefing facilities.

b. Ability to start mission rehearsal no later than 54 hours after notification (48 hours is preferable). This assumes a minimum of 72 hours between tasking and deployment, 12 hours of crew rest prior to deployment, and 6 hours of rehearsal time.

c. Ability to accept real-time updates to the simulation based upon intelligence data, reconnaissance photography, etc.

d. Security provisions to whatever level necessary for the rehearsal.

e. Ability to provide real-time weather information for update into the rehearsal scenario.

f. Simulator-unique functions of freeze, reposition, record/playback, performance evaluation, condition override and mission critical faults, malfunctions, and emergencies. (The Working Group considers, however, that all except record/playback and performance evaluation should be avoided in true mission rehearsal simulation.)

g. Risk/feasibility assessment (defining success for the mission).

h. Ability to reconfigure mission equipment in the rehearsal to the same configuration as will be in place during the mission.

<u>Tactics</u>. Tactics requires units coordinating activities with other units. All services today practise what is known as Combined Arms Warfare (CAW). Air, land, and sea forces work together in a supportive and complementary role to assure mission success. This requires that devices used by a particular branch of the armed services must not only link and work with each other, but must also link and work with the devices of other branches and with those of allied forces. "Every action of every soldier, system, or unit reinforces the effectiveness of other soldiers, systems, or units to create an overall violent effect" (US Army Staff Officers Handbook).

Exploitation of appropriate tactics thus imposes the following requirement:

- Networking between participants to allow air, land, sea coordination for joint operations within services, between services, and with allies.

<u>Uncertainty</u>. All three forms of uncertainty (situational, probabilistic, and operational) are required in order to provide realistic stresses and mission workloads and to support the "what if" aspect of the rehearsal.

The requirement to provide uncertainty imposes the following requirements:

a. Uncertainties appropriate to the mission including situational, probabilistic, and operational uncertainty.

b. Stress workloads similar to mission stresses.

This brief review emphasises the variety of features that need to be replicated in mission rehearsal simulation. Some are discussed in this report, such as scene generation and correlation, but others, such as behavioural models of enemy forces, are not covered here.

CHAPTER 2

OPERATIONAL NEEDS

CONTENTS

1 SUMMARY

This chapter summarises the need for the further development of 'mission rehearsal' simulators, capable of supporting the low altitude, high speed training task with as much realism as advancing technology can, or may sensibly be predicted to, provide. It identifies the various types of Offensive Support and Air Defence missions that need to be simulated and breaks them down to a sequence of characteristic mission management 'events' or mission task elements. An attempt is then made to translate these detailed mission events into broad-brush simulator requirements. Finally, some thoughts on probable training support needs and facilities, for the kind of advanced mission rehearsal systems postulated in this report, have been included to complete the chapter.

An Annex is included which describes a typical training philosophy and discusses the employment of synthetic training equipment.

The first part of this chapter is written in a point (bullets) brief style for ease of assimilation by the reader.

2 INTRODUCTION

A requirement for the rehearsal of combat mission profiles in simulators exists because:

- Generally, training flights cannot be flown over the assumed combat areas.

- Peacetime training flights cannot be flown under realistic combat conditions due to the lack of threat, friendly force participation, NBC and ECM. (Note: the most representative operational training, available in peacetime, is that offered in the USAF FLAG exercises.)

- Environmental considerations in peacetime have led to increasing restrictions being placed on low-altitude flying in many countries.

Limitations include:

-- Reduction in amount of low flying time.

-- Speed restrictions.

-- Raising of minimum altitudes.

-- Reduced number of low flying areas.

-- Reduction in night flying hours.

3 MISSIONS

A future 'mission rehearsal' system must be capable of simulating the following types of missions, which involve, or could involve, elements of low-altitude (ie. less than 2000 ft above ground level, agl) high speed flying:

- Tactical Nuclear Strike (singleton missions).

- Offensive Counter Air (OCA). Missions mounted to destroy, disrupt or limit enemy air power as close to its source as practicable. To prosecute OCA operations, the following low-altitude/high speed offensive roles may be employed:

  -- Attacks against enemy airfields and Command, Control, and Communication (C3) facilities.

  -- Suppression of Enemy Air Defences (SEAD) to disrupt, degrade, and destroy the enemy's AAA/SAM sites by the use of missiles and/or electronic jamming.

- Defensive Counter Air (DCA). DCA operations comprise all measures and means designed to nullify or reduce the effectiveness of hostile air action. The primary aim of these operations is to inflict the maximum attrition on the enemy's air force. DCA missions that require fighter aircraft to operate in the low-altitude/high speed regime are as follows:

  -- Interception. Can be carried out autonomously or with the assistance of air defence radars, including Airborne Early Warning (AEW).

  -- Combat Air Patrols (CAPs). Fighter CAPs are mounted over an objective area, over the Force being protected, over a critical area of a combat zone, or over an air defence area, for the purpose of intercepting and destroying hostile aircraft before they reach their targets.

  -- Fighter Escort. May be needed to support other aircraft carrying out offensive, defensive or combat support tasks.

- Land/Air Operations. The inherent flexibility, reach and speed of air power allows combat aircraft to project firepower rapidly against enemy land force targets, both laterally and in depth. Land/Air operations include the following combat air power roles:

  -- Air Interdiction (AI). Missions conducted to destroy, disrupt, neutralise or delay the enemy's military potential before it can be brought to bear effectively against friendly forces. Achieved by attacking lines of communication and second echelon forces behind the battle area.

  -- Offensive Air Support, includes Close Air Support (CAS) and Battlefield Air Interdiction (BAI). Operations against hostile land targets which are either in close proximity to friendly forces or in a position to affect them directly. These missions require either joint planning and co-ordination or detailed integration with the fire/movement of friendly land forces.

  -- Armed Reconnaissance. Missions flown with the primary purpose of locating and attacking targets of opportunity, for example enemy materiel, personnel and facilities in assigned general areas or along assigned ground communications routes.

  -- Tactical Air Reconnaissance. Missions to gather pre- and post-attack intelligence data on enemy targets.

- Maritime Operations. Anti-Surface Maritime Air Attack missions are normally carried out in response to short notice requests by the sea commander to counter short-range enemy surface threats, or for operations close to the shore to counter enemy amphibious forces. Targets are normally attacked using missile-

armed Strike/Attack aircraft with attack support from Maritime Patrol Aircraft.

4 GENERAL OPERATIONAL REQUIREMENTS

An advanced 'Mission Rehearsal' simulator must be capable of providing training in mission events which could not be sensibly or actually flown under peacetime conditions. For it to be an effective training tool it must be capable of simulating the following:

- Realistic low-level flying down to 50 ft by day and 100 ft by night, at maximum speeds defined for each aircraft type.

- As close to all-round visual field-of-view as possible, in both day and night conditions.

- All weather, including localised conditions and seasonal differences.

- Advanced terrain simulation of the area to be covered on the actual mission and which can realistically be used for terrain masking.

- Good natural lighting effects for the visual system, to include real time transitions from day into night and vice-versa. This should include use of Night Vision Goggles (NVGs) and Forward Looking Infra-Red (FLIR).

- Capability of flying close formation and tactical formation on other aircraft, regardless of type or nationality, by both day and night.

- A wide cross-section of ground, maritime and airborne targets, together with their corresponding electronic signatures, engagement ranges, representative engagement rules, counter-measures and realistic camouflage.

- A comprehensive suite of air and ground threats with representative and interactive Electronic Warfare (EW) counter programmes.

- Dynamic attack radar system tied into an advanced digital landmass simulation, for:

  -- Fixing.

  -- Attacking surface targets.

  -- Low level air to air engagements.

- All simulated sensors need to be carefully synchronised with one another to avoid mismatched and conflicting information being presented to the crew, unless such effects are genuine.

- Weapon characteristics:

  -- Capable of 'loading' all current in-service weapons.

  -- Software capacity to incorporate projected advanced weapon systems.

  -- Realistic simulation of weapons effects and aircraft self-damage.

  -- Full retention of visual cues throughout all weapon delivery profiles (with good visual definition and detail out to 2 nm around the target to be attacked).

- Provision for simulating NBC conditions with appropriate aircrew clothing and equipment.

5 SPECIFIC 'MISSION' REQUIREMENTS FOR A SIMULATOR

5.1 Preparation

- Planning. Probably carried out in the squadron facilities with access to intelligence, meteorological and theatre databases.

  -- Mission data transfer to 'aircraft' nav/attack system on arrival at simulator.

  -- Full mission briefing (including up-to-the-minute intelligence situation).

5.2 Flying the Mission

- Release and Safe Lane departure.

- Transit to refuelling area, normally at high level.

- Air-to-Air Refuelling (AAR). Fill to full fuel whilst continuing to simulate the handling characteristics of a full weapon load; sequence as follows:

-- Rendezvous (RV) with tanker, normally effected in close formation.

-- Formate with tanker and other aircraft around it.

-- Make refuelling contact. (Note: simulator fidelity must be sufficient to ensure that the danger of imparting negative learning to the crew does not become a factor.)

-- Disconnect.

-- Depart refuelling area en-route.

Note: Although the departure and AAR are not specifically low-altitude events, they do nevertheless constitute part of the overall mission and as such must be rehearsed along with the rest so as to provide realistic timescales and to ensure that, as on the live mission, the crews are faced with timing and co-ordination problems to resolve.

The remainder of the mission is described under the headings: ingress, attack phase, egress, recovery and debrief.

- Ingress. Fully co-ordinated ingress to attack, with Forward Line Own Troops (FLOT) crossing, minimum risk routing and employment of current tactics in response to air and ground threats. Considerations include:

  -- Representative Operational Low Flying (OLF).

  -- Attack formations will fly in tactical mutually supporting elements of two aircraft up to designated split points or Initial Points (IPs) using one of the following formation types:

    --- Defensive visual battle (3-5 km line abreast).

    --- Parallel track (5-10 km line abreast, not necessarily in visual contact, using Terrain Following Radar).

    --- Trail (normally used to achieve accurate over-target timing).

    --- Fighting battle/tactical, 200 metres apart, 60 deg swept on element leader, provides manoeuvre flexibility in low-level terrain masking flight.

    --- If necessary close formation could be used, although it is not a tactically viable formation for low level.

  -- Navigation at low level is carried out using one, or a combination, of the following techniques:

    --- Visually using map and stopwatch.

    --- Using the aircraft's integral navigation system.

    --- Sensor aided (Radar, FLIR, GPS, LLTV, NVG).

    --- Reversionary mode navigation (ie. with degraded main navigation equipments).

  -- Interception, interrogation, identification and engagement of airborne targets Beyond Visual Range (BVR).

  -- Interception, interrogation, identification and engagement of airborne targets Within Visual Range (WVR).

  -- Air Combat Manoeuvring (ACM) capability.

  -- Integration of the following:

    --- Terrain Following Radar (TFR).

    --- Terrain Reference Navigation (TRN).

    --- Forward Looking Infra-Red (FLIR).

    --- Low Light TV (LLTV).

    --- Night Vision Goggles (NVG).

    --- Global Positioning System (GPS).

- Attack Phase. Fully coordinated attack using cooperative techniques and Suppression of Enemy Air Defences (SEAD) tactics. Considerations include:

  -- AWACS or Tactical Direction could be

required.

-- Stand-off weapons, eg. HARM, ALARM, Sea Eagle, Kormoran.

-- Realistic radar warning and missile launch indications.

-- ECM/Chaff/IR Flare/Evasion/Terrain masking.

-- Visual presentation of surface to air weapons (SAMs in flight and AAA tracer).

-- Visual representation of other aircraft attacking and the effects of their weapons, including debris-induced damage effects and target obscuration by smoke.

-- Simulation of Laser for target designation, ranging, weapon delivery and assessment of damage. Use of laser target marking information from other aircraft in a designating role.

-- Console indication of weapon delivery accuracy and scoring.

Egress. Repeat of ingress scenario plus the following:

-- Use of minimum risk egress routing and heights.

-- Interactive IFF procedure.

-- Mission effectiveness reporting.

Recovery.

-- Safelane procedures through the High Level Missile Engagement Zone (HIMEZ) into the recovery base's Short Range Air Defence Engagement Zone (SHORADEZ).

-- Interactive simulation of friendly air defence system.

-- Close formation recovery.

-- Flying/systems degradation induced by battle damage.

-- Simulation of recovery base under attack or damaged requiring the use of Minimum Operating Strips (MOSs) and Dispersed Operating Bases (DOBs).

-- approach and landing using NVG, FLIR and LLTV.

- Debrief. Comprehensive debrief of sortie using selected playback as required.

6 TRANSLATION OF OPERATIONAL NEEDS INTO DETAILED SIMULATOR REQUIREMENTS

- A full colour visual system giving a 3D textured display, capable of providing low-level visibilities of up to 10 nm overland and 20 nm over the sea.

- In order that the visual system can be used for representative terrain flying it must provide terrain contours at intervals of at least 200 ft with gradients of 45 degrees or more within half nm of track.

- Full motion system to include:

  -- Variable ride characteristics (gusts, buffet and turbulence).

  -- 'G' force cueing probably through a 'G' seat system (seat cushion inflation, strap tightening and G suit inflation).

  -- Weapon release vibration and disturbance effects.

- Realistic sound system to augment and enhance motion effects.

- The simulator must have special-to-type cockpits and simulate all relevant aircraft systems.

- Full simulation of aircraft performance up to and exceeding controlled flight boundaries.

- Full aerodynamic modelling for all configurations (including asymmetric to simulate stores hang-ups).

- A database system capable of representing as

many global area scenarios as current technology and intelligence allows.

- A comprehensive 'threat' library of friendly and potentially hostile equipment parameters.

- Interactive EW/ECM.

- Interactive Pilot Station (IPS), or stations, for wingman and scenario interplay.

- Personal aircrew equipment and environmental conditions to be as close as possible to those worn and experienced in the actual aircraft.

7 MISSION SUPPORT FACILITIES AND FUNCTIONS

Mission rehearsal may be accomplished in a simulator of the type described above. Additional supporting functions and facilities are needed, however, to make it an efficient training tool. To maximise pilot/crew in-the-cockpit training, basic functions of mission planning, briefing, execution and debriefing require separate facilities. The operator station will provide the necessary scenario initialization and control functions.

The complexity of the simulation may run from a single aircraft mission to full air battle, including ground scenario. The report of the AGARD Workshop on Low-Level Flight Training (AGARD, 1990) cited examples of current and projected complexity to include one self-contained single cockpit, single cockpit with integrated work stations for wingmen, multiple full-cockpits with friendly and threat aircraft and ground defences ultimately to **networked** simulations with many air and ground elements for battle level operations.

7.1 Mission Preparation

A mission rehearsal simulator only becomes useful when realistic, timely, non-repetitive scenarios are created for it. While standard routes may be useful for initial training, combat training demands varying scenarios for each flight. Provision must be made to store scenarios for purpose of re-training or the use of similar basic scenarios with only target changes for same day use.

Every mission originates with an Air Tasking Order (ATO). As soon as the ATO is received, the crew will commence their mission planning sequence. The ATO includes the target(s), time on target, package composition, weapons, support aircraft, communications, safe routes, and identification procedures. In addition an intelligence and threat briefing, including weather, electronic warfare and safe areas should also be given. Creation of the ATO and briefings by appropriate staff on a daily basis would serve to create realistic training opportunities for those personnel as well as provide pertinent data for the simulated mission. As far as practically possible, the actual base operations and intelligence staffs should be used to brief pilot/crews for mission rehearsal sorties. Of course, simplified operation without all of the normal support would be required for routine training or out of normal operating hours training.

7.2 Initialization

Clearly, the initialization of the simulator to the assigned scenario will take a finite amount of time. It is preferable that this period should not be greater than 30 minutes. Whether the initialization task is done manually, with a pre-stored/loading capability, or automatically connected to the tasking database, the method of entry will determine the time taken.

More complicated scenarios will require set-up of ground threats, attacking aircraft, mission support positioning, positioning of ground moving targets, friendly forces, camouflage, and so on. Time required for set-up will be in direct proportion to mission complexity. The operator may use the start-up and taxying ground time to complete this task.

7.3 Mission Planning

The crew members should receive the ATO with the standard amount of planning and preparation time available before flying the tasked mission. If the simulator is close to squadron assets, the planning phase should be carried out at that location. However, for many crews, travelling to a centralized simulator will be necessary; in this case these facilities must provide adequate mission planning facilities. The advent of automated, database-oriented mission planning systems will also require these facilities to be available.

Such systems will includes data transfer capability identical to the aircraft. The level of sharing of database information with such a planning system could create additional speed of operation but the interface used must appear to be identical to the actual equipment used by the aircrew on their squadrons.

7.4 Mission Briefing

Standard squadron flight briefing rooms with boards, maps and appropriate planning aids must be available. A range of room sizes will be required to accommodate anything from a single crew and instructor/operator to a full-scale multi-ship support package briefing. Future facilities may require telephone or video conference briefings, to reach networked simulator participants, for larger battle level exercises.

The essential briefing for the control interface personnel must be separate from the aircrew and could occur during mission planning using the aircrew briefing facilities. Again, the complexity of the system and numbers of operators will determine the detail of this briefing. A written plan would facilitate proper timing of critical events but some orchestration to achieve maximum training would be required.

7.5 Mission Execution

The aircrew should be allowed start-up, taxying, mission data loading and end-of-runway activity time as for a normal live-flight. This includes loading of keys for encryption, synchronizing equipment and ground electronic protection checks. Failure modes with correction capability would provide realistic feedback and opportunity for wartime go/no-go decisions. Furthermore, an ability to reposition a flight or simulator to practice an area of poor performance should be included. The console operation should provide rapid input to accomplish this task. Provision and use of event markers would be essential to locate specific areas in the mission to be debriefed in detail.

Control of simulated failure of equipment through normal operation or battle damage, air and ground threat, jamming, weather, rendezvous with support aircraft (tanker) and communications with the AWACS can keep a single instructor/ operator extremely busy. Monitoring mission progress with the ability to mark and record events should be the simulator instructor/operator's primary concern, with control of the scenario being secondary.

7.5.1 Target Variables

Control of movement, defences, weather, friendly troops, air or ground forward air controller or general creation of a fluid situation will require individual operator control or computer-driven models. Highly variable target situations may be matched to the mission of the aircraft also, with the close air support being at the most variable end and strike mission at the other. Either computer-controlled or workstation-flown threat aircraft could be displayed visually or on the various simulator sensors.

7.5.2 Sensor and Weapon Variables

Varying climatic conditions can create very different pictures for infrared or low light video sensors and weapons. Proper simulation, with expected camouflage tactics, will be required to ensure realism. Weapon effects with capacity for real time damage assessment and re-attack should be included. This would require changes of the visual or sensor database to show damage of the target based on probability of kill and weapon delivery accuracy.

8 DEBRIEF

A separate debrief and playback facility is required because of simultaneous training occurring in other parts of the facility. AGARD (1990) recommended ACMI-type mission recreation capability. Possible playback of sensor video would also maximize training. Size of the debriefing facility would be determined by the size of the total simulation. Instructor/operators could provide feedback on aircrew performance by highlighting those areas marked during the mission. Other operators could provide feedback on any reaction to their specific areas of expertise. Review of weapons scoring and bomb damage assessment could be available. Threat reactions and tactics could be reviewed using the ACMI playback. An overall score using previously established criteria would provide independent, objective feedback.

The instructor should have the ability to control the replay by rapidly advancing throughout the mission. Mission event markers could facilitate the speed of movement. If simulators are networked, telephone or video conferencing may be required for the players to contribute their debrief.

9 CONCLUSIONS

This chapter has defined in a logical and comprehensive manner the mission task elements that need to be simulated in a Mission Simulator. It has translated these into general and specific requirements and discussed broad aspects of the support facilities required. Mission simulation is a complex task, and contains much more than just the low altitude, high speed component.

ANNEX A

TRAINING PHILOSOPHY

A.1 BACKGROUND

In order to understand the terms 'mission training' and 'mission rehearsal', as used in the simulator context, some background information on typical training philosophy and the employment of synthetic training equipment (STE) is necessary. The information that follows relates specifically to Royal Air Force (UK) training methods but in general terms these are broadly similar to those employed by many other air forces.

The overall aim of pilot/crew training in the RAF is to produce an independent minded pilot/crew with the skills needed to fly the aircraft to its limits with accuracy and confidence, without undue reliance on external assistance or electronic aids and down to the weather minima for the relevant type. Overlying this is the need to complete that training in the most cost-effective manner. In trying to achieve this aim, the RAF operates within the following guidelines:

- The number of training phases should be the minimum to train effectively.
- The number of aircraft types should be kept to a minimum.
- The maximum amount of training should be given on the least expensive aircraft.
- Synthetic training equipment (including simulators) should be used to the limit of their potential for each stage of flying training.

A.2 SYNTHETIC TRAINING AIDS

It is an accepted fact that complex aircraft and weapon systems require comprehensive crew training and, in peacetime, such training is a full time occupation. Live training using operational equipment (OE) is very expensive in both aircraft and support costs, and frequently has an adverse effect on the environment. Moreover, in many cases, OE cannot be used safely for full crew training. An alternative way of achieving a high level of proficiency without the penalties of using OE is to use Synthetic Training Equipment (STE). The guiding principles in the use of STE is to conduct as much training as practicable on the cheapest possible device.

While it is widely accepted that simulation is neither a complete nor automatic alternative to 'live' training, there are cases where effective training can only be carried out by simulation. Nevertheless, current thinking does not envisage increased training on simulators substituting for actual flying time for trained aircrew, which military judgement regards as already at the minimum necessary for flight safety, operational effectiveness and aircrew motivation.

A.2.1 Benefits of Using Synthetic Training Equipment

Training usually involves combined use of suitable simulators and parent equipment. Simulators can provide a controlled training environment and the ability to conduct training gradually in relation to trainees' learning capability. Complete lessons or particular parts can be recorded to permit feedback to the trainee.

Other particular benefits of simulators are:

- **Safety** - simulation provides a safe training environment for rehearsing tasks, abnormal situations and emergency drills, which would otherwise be considered too hazardous to the trainee or to third parties.
- **Cost** - Generally, capital costs of simulators are often lower than those for the parent equipment. The normal operating costs of a simulator are usually about 10% of the operating costs of the parent equipment. Where simulators substitute for training on the parent equipment, they effectively extend the life of that equipment. Cost is linked to safety in that the early stages of training are characterised by errors and by accidents, with cost in terms of human life and loss of, or damage to, the parent equipment.
- **Impact on the environment** - simulation can reduce the need for 'live' training which, increasingly, is being blamed for causing damage to the environment.
- **Practicality** - the increasing operational capability, particularly in terms of range of weapons systems employed, is a constraint on 'live' training. Also, some training

requirements can only be met by simulation, for example the ability to practice mission training in a hostile environment. Simulation also allows training to continue regardless of weather or time of day.

A.2.2 Training Functions of Simulators

Simulators are fundamental to virtually all aircrew training. They are used at every stage of training (figure 2-1) to fulfil some or all of the following functions:

- Conversion training, from one aircraft type to another, of pilots/crews.
- Continuation training of pilots/crews.
- Evaluation and standardisation of pilots/crews.
- Development and evaluation of tactics and procedures.
- Practice of war roles.
- Mission rehearsal.
- Evaluation of modifications to aircraft applications software.

A.2.3 Types of Synthetic Training Equipment

The following types of aircrew synthetic training aids (ASTAs) are currently in use with the RAF:

- Classroom training aids or computer-based training (CBT).
- Part task trainers (PTTs).
- Cockpit procedures trainers (CPTs).
- Basic flight simulators (BFSs).
- Full mission simulators (FMSs).

A.2.4 Description of Synthetic Training Equipment Types

The following paragraphs briefly describe these various types of STE.

Computer-Based Training (CBT). CBT or Computer Aided Training (CAT) has been developed to combine an advanced classroom visual aid, with an interactive learning medium for individual students. Most systems consist of individual workstations based on desktop computers driving one large or two smaller display screens; each set of workstations is linked to an instructor's console with a large screen monitor. The speed of modern computer systems, together with high resolution colour graphics, enables complex aircraft systems to be animated and simplified for the student. Designing and generating the courseware can be very time-consuming but, once installed, CBT allows students to conduct self-paced learning with minimal instructor participation.

Part-Task Trainer (PTT). Once basic theory has been learned, possibly with the help of CBT, a second range of devices, PTTs, can be used. These trainers provide 'hands-on' instruction to promote familiarisation with the parent equipment. PTTs are usually working models of a single aircraft system although, in some cases, a PTT can cover a number of related systems.

Cockpit Procedures Trainer (CPT). CPTs are accurate replicas of their respective aircraft cockpit but generally have no flight model, visual system or motion. However, some systems may be modelled to allow, for example, engine starts to be practised. CPTs are primarily used to introduce students to the full cockpit, and to develop familiarity with the controls and associated check lists. Limited inter-active training is usually possible, and some instructor involvement is possible to present the crew with emergency situations to resolve. In multi-crew aircraft, the CPT permits the first stages of Crew Resource Management (CRM) training to be conducted.

Basic Flight Simulator (BFS). Full system representation, visual systems and motion cuing differentiate the BFS from the CPT. A BFS is designed to provide an environment in which a student pilot (and crew if applicable) can be instructed in the following:

- Conversion to type.
- Basic handling skills and safe operation of the aircraft.
  - Cockpit familiarisation.

- -- Cockpit normal and emergency drills.

- Navigation skills.

- Instrument flying.

- Consolidation of all systems operations except for training in the use of weapons and tactical applications of aircraft sensors.

There should be no requirement for a BFS to be used for squadron/wing skill training or mission rehearsal. It could, however, be used for instrument rating tests if so certified.

Full Mission Simulator (FMS). A Full Mission Simulator allows the crew to undertake complete and totally realistic operational sorties, including simulated release of weapons, in an environment containing hostile threats, simulated targets and friendly forces. The FMS, (or rather the advanced technology versions of it), is the only type of equipment considered suitable for mission training/mission rehearsal. The advanced technology FMS, postulated in this report, will be required for the following purposes:

- Conversion to type training.

- Continuation training (CT).

- Training to Combat Ready (CR) status.

- Crew evaluation and standardisation.

- Development and evaluation of tactics and procedures.

- Practice of war roles (mission training).

- Mission rehearsal, which includes such aspects as:

  - -- Training in hostile, electronic and ground/air threat environments.

  - -- Co-operative training (formation flying and multi-aircraft operations).

  - -- Training against multiple targets.

- Evaluation of modifications to aircraft applications software.

A.3 OPERATIONAL CONVERSION TRAINING

By the time crews arrive at a fast-jet operational conversion unit (OCU) they will have been in the training system for some considerable time (typically two years for pilots and one year for navigators). They should be attuned to the intensive demands of learning to fly and fight a modern combat aircraft. The OCU courses they undertake are generally divided into two phases, a conversion to type followed by a tactical phase.

The conversion phase will concentrate on the aircraft's systems and handling characteristics, and on instrument and formation flying. Training courses for two-seat, as opposed to single-seat, aircraft will include crew cooperation as part of the syllabus and the newly partnered crews will complete the OCU together. Both pilots and navigators will be expected to have a good working knowledge of each other's tasks and to share responsibility for the effective and safe operation of the aircraft. Particular emphasis is put on the use of the various forms of STE, previously mentioned, during this important familiarisation phase.

The bulk of the tactical phase will be concerned with weapon system manipulation, weapon delivery and air combat manoeuvring (ACM). As the course progresses, basic tactics are combined with weaponry events into increasingly complex sorties. The final stage of air to ground courses will involve planning, briefing, flying and debriefing a sortie which includes simulated attack profiles (SAPs), fighter evasion and live weaponry on bombing ranges. Air defence (AD), or fighter, courses will inevitably involve more simulated air to air combat and radar intercept work. The final stage of the AD courses will include complex interception and simulated combat procedures. Once again, if Full Mission Simulators are available they can be put to good use throughout the advanced OCU training phase.

The graduation standards of OCU students are high and as a minimum they should be capable of leading a pair of aircraft, although normally further training on their first squadron will be essential.

A.4 TRAINING ON THE SQUADRON

Shortly after arriving on their first squadron, having gained limited theatre and operating procedure experience, the pilot/crew will be declared Limited Combat Ready (LCR). LCR signifies that, if called upon to do so, the crew could successfully complete a

simple wartime mission as a wingman (ie. not as the leader). Then, following an intensive work-up period that includes live flying and a variety of FMS sorties, the new crew will be declared Combat Ready (CR). CR crews are capable of flying all missions within the squadron's declared role.

During peacetime the majority of sorties flown in the FMS will be of relatively short duration, between 1 and 2 hours, to practise a cross-section of the skills and techniques applicable to the aircraft type and its role; this type of simulator sortie is termed **Mission Training**. The most complex and indeed the highest level of mission training is termed **Mission Rehearsal**; the means by which some measure of mission proficiency and practice can be achieved by using the planned scenario for a particular operation.

Mission Rehearsal allows the crew to:

- Practise under actual time and distance constraints.

- Practise over same or similar terrain to that to be encountered on the mission.

- Consider alternative courses of action.

- Adapt to changing circumstances during the mission.

Some contingency mission rehearsal will take place in the FMS during peacetime to develop missions against actual targets in the countries of the most likely future opponents. Also, if crews are designated to 'stand on' (earmarked for) specific wartime targets they will in all probability be required to fly simulated full mission rehearsals against those targets once or twice a year for currency and updating purposes.

During Transition to War (TTW) and following the outbreak of hostilities the majority of FMS effort will be devoted to crews flying full mission rehearsals in preparation for their actual operational missions (ie. fine tuning). In the most likely event of the squadrons/wings being detached and forward-based they would wish to take their 'air portable' FMS with them in order to continue the mission rehearsal and tactics development process against the specific enemy forces and targets to be faced.

Fig 2-1 shows the order in which the various pieces of STE are utilised in the fast-jet training process and the relationship between mission training and mission rehearsal.

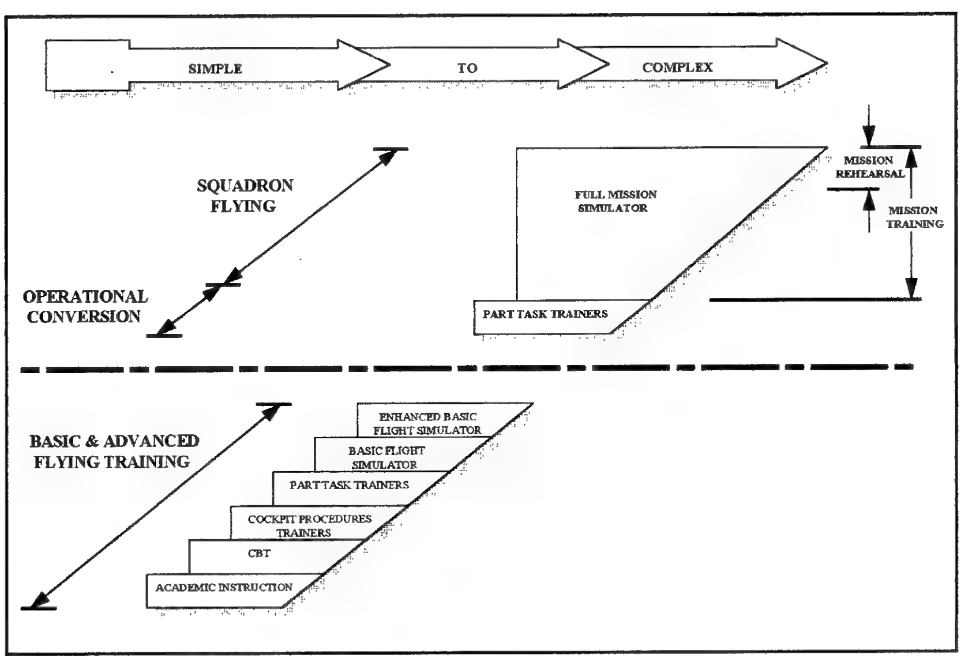

Figure 2-1 Utilisation of Synthetic Training Equipment

CHAPTER 3

MISSION SIMULATORS

CONTENTS

1 INTRODUCTION

This chapter provides an outline definition of a typical mission simulator to serve as background information for the detailed review of simulation technology in later chapters.

The term Mission Simulator is used to describe a wide variety of training equipment aimed at providing training for the many missions that armed forces personnel could be called upon to undertake. To a very large extent the complexity of the intended mission and the sophistication of the weapon system determine the complexity and sophistication of the mission simulator used for the training task. As this report is focused on the use of simulators for the training of the very demanding low level flight mission, the definitions and descriptions that follow in this chapter address the essential characteristics of aircraft mission simulators which could support this type of training.

Mission simulation in this context implies much more than the capability to support the training of flight at low level. To be eligible for the title Mission Simulator the training device must support the training of the total mission including the full simulation of the aircraft, its weapons and systems and the external environment within which the aircraft and crew must perform their intended mission. This external environment encompasses the geographical and atmospheric conditions and the distribution, composition and actions of friendly and opposing forces.

2 MISSION SIMULATOR COMPONENTS

A Mission Simulator is a complex device, arguably more complex than the aircraft that it seeks to represent. This is because it must not only faithfully reproduce the performance of the aircraft and aircraft systems but also adequately represent the external environment within which the aircraft must operate. The essential components of a Mission Simulator include the representation of the air vehicle itself, together with all of its various subsystems, the representation of the cues present in the real world and the representation of other players within the simulated scenario. To support these representations requires the creation and maintenance of various databases so that the characteristics of the real world mission as perceived by the aircrew are mirrored

as closely as possible by the perceptions received in the Mission Simulator.

The components of a Mission Simulator are typically as listed below:

(a) A replica aircraft cockpit, including simulated and actual aircraft parts and avionics;

(b) A computer system or systems and interface, or linkage, which provides the simulation models, drives the replica cockpit systems and controls all the simulation subsystems such as motion systems, visual systems, environment models and scenarios;

(c) A motion cuing system, either a g-seat/g-suit, a motion platform, a seat shaker, or a combination of these;

(d) A computer image generator, which generates visual images of the external environment to be viewed through the display system and, in many cases, additional sensor imagery for display on the replica cockpit avionics displays;

(e) A visual display system which presents the computer generated image to the aircrew, and may be a direct viewing system with screens or domes or an indirect viewing system with mirror/beam-splitter systems or helmet-mounted displays;

(f) A Digital Radar Landmass Simulator (DRLMS), if radar is fitted in the aircraft, to present a radar image to the replica cockpit radar display;

(g) An Electronic Warfare (EW) signal generator if an electronic warfare system is fitted in the aircraft;

(h) An instructor facility to allow control of the training mission;

(i) A brief/debrief facility to allow for trainee pre-flight briefing and post-flight debriefing and sometimes mission planning; and

(j) Database and scenario development facilities which allow the simulator user to create and maintain visual and other databases and create, update and execute mission scenarios.

These key components are discussed briefly here and the critical areas are elaborated further in later chapters.

2.1 Vehicle and Systems Simulation

In most cases the simulation host computers execute the software necessary to model the performance of the aircraft and that of its various systems, though in some cases specialised hardware is required to complete the process, such as a DRLMS system or EW signal generator. Computer operating systems, being general purpose, are typically enhanced with some form of simulation executive which will support the somewhat special requirements of the simulator environment, such as precise scheduling of all the simulation software code to achieve real-time performance.

Accurate modelling of the aircraft's handling characteristics and on-board systems is perhaps the most obvious requirement of a Mission Simulator. In fact many older devices fall short of this basic characteristic and receive poor aircrew acceptance because the simulator does not behave like the aircraft.

2.1.1 Flight and Flight Control

The handling characteristics of a simulator are directly related to the accuracy of the simulation of the aircraft flight dynamics and flight control system. Adequate representation of a high performance combat aircraft, in all possible flight conditions, requires a very high fidelity mathematical model of the aircraft aerodynamics, with a description of the aerodynamic terms, both first and second order, over a wide range of angle of attack and sideslip, etc. In combat aircraft the characteristics of the vehicle at the edge of, or even beyond, its design flight envelope is of great importance as combat flying can often require extreme manoeuvres to achieve a mission objective in the face of a determined adversary. Engine performance and response data must also be accurate.

The characteristics of the flight control feel system need also to be represented completely. Control forces, such as breakout forces, stick force/g, limits of travel, must be accurately simulated. Inadequate simulation of flight controls is immediately recognised by the aircrew and can lead, in the extreme, to handling problems such as Pilot Induced Oscillation (PIO), especially when trying to aim weapons or fly in close formation. Reversionary modes must also be fully modelled as the effects of simulated battle damage can lead to control system failure.

Surprisingly, the development of comprehensive data packages for combat aircraft which provide the Mission Simulator developer with the data necessary to support

such modelling is a somewhat less well-defined process than that which has been in existence for some time (IATA, 1993) in the commercial airliner simulation world. In the commercial environment, aviation certification authorities such as the FAA and others control simulation standards by strictly relating the training credits that can be achieved on a simulator to the fidelity of the modelling. These standards are typically represented by the FAA document AC 120-40B (FAA, 1989). There is very close liaison between international authorities and hence the standards employed are essentially common throughout the industry (see IQTG, 1992). Military authorities have yet to establish such a unified approach. Indeed, this would be a worthy subject for an AGARD working group.

The performance of modern computer systems and the continual improvement in their price/performance metrics now allow modellers to fully represent the available aircraft data in the simulation. To achieve latency characteristics which match those of the aircraft, high iteration rates are required in the flight and flight controls simulations. Typically, flight models are being executed at 60 Hz, with ground handling models running at up to 300 Hz and flight control feel system models running at several kHz, to achieve an adequate match with the real world.

2.1.2 Systems Simulation

To support the training of systems and weapons management tasks associated with the performance of a mission, full simulation of the various aircraft systems is required. The simulated cockpit environment is a fully functional replica of the actual aircraft in terms of its appearance to the aircrew, its effects on the vehicle and its response to aircrew interactions.

Typically the Mission Simulator cockpit consists of both actual aircraft hardware and simulated parts. For example, air driven instruments, though increasingly rare in a modern cockpit environment, are, when found, represented by a simulated part which is driven electrically.

The issues associated with the use of actual aircraft avionics hardware in a simulator environment are addressed in chapter 7.

2.1.3 Weapons Systems Simulation

Weapon systems simulation is a key area in a tactical simulator and one where there is often variation in the extent of the modelling. In all cases the interactions of the weapon with the crew and other aircraft systems are represented so that all actions that are required to initiate a weapon release are fully supported in the simulator. Weapon flyout is a somewhat different case. Older simulators would typically represent the performance of the weapon after release in a statistical fashion, based upon the parameters at the time of release. Thus, for example, the performance of a heat-seeking missile against an air threat would be based on how well positioned in the release envelope the missile was at the point of launch. Ballistic weapons would be treated more precisely because of the relatively simple computations required to determine impact point.

Such simplifications were dictated in the past by limitations in computer performance, a factor which is no longer the case. Thus modern Mission Simulators increasingly incorporate weapons simulation of much greater sophistication which include the performance of the weapon guidance system and fusing, consider the effect of target manoeuvre and countermeasures and fly the weapon from launch through to detonation.

The electronic warfare environment has a critical impact on tactical aircraft operations, forcing, for example, the adoption of low level flight to avoid detection by hostile radar systems. Thus the simulation of the aircraft EW systems, both detection systems and countermeasures, is necessary to provide full mission training. Due to the nature of the equipment involved, the simulation of radars, Radar Warning Receivers (RWR) and other EW systems typically involves special purpose signal processor hardware such as a DRLMS or an EW signal generator. These signal processor systems are capable of supporting the very high computational rates necessary to generate real time radar images and simulate the presence of multiple radar emitters.

2.2 Pilot Cuing Environment

The pilot cuing environment is the sum of all the various inputs that the Mission Simulator provides to the aircrew. This cuing environment includes visual, tactile, motion, audio and olfactory cues. In most cases the olfactory cues are not represented, ie there is no jet fuel smell or other smells provided, though some commercial airliner simulators can generate smoke to test crew reaction.

2.2.1 Visual Cues

The most important of the various cues are those which present visual stimuli to the aircrew, particularly the view of the outside world created by the visual system.

Other visual cues are those provided by the various cockpit indications and those which represent aircraft sensors such as FLIR systems and radar. Correlation of all these visual inputs is essential as cue mismatches can lead to crew disorientation and at the very least to a lowering of crew acceptance of the Mission Simulator.

Correlation of cockpit instrument indications with the visual scene is relatively straight forward, essentially requiring correct timing of responses in the cockpit with the movement of the outside images. Correlation of sensor images is somewhat more complex due to the performance differences of the sensors. Radar systems, for example, present a plan view of the world to the crew. This plan view must correlate accurately with the scene presented by the visual system so that coordinated crew actions, such as the designation of a visual target using the radar, can be achieved.

Visual scene simulation involves the generation of an image in a computer image generator (IG) and the display of that image using some form of display. Mission Simulation places significant demands on these systems as the need is to provide a visual cuing environment which maximises the transfer of training benefit to the crew of the simulator. The current state of the art in visual systems does not allow the real world scene to be fully represented in the simulator. Indeed, visual systems are not expected to reach such an elevated state of performance for some time to come. The challenge for the Mission Simulator developer is to maximize the cuing benefit and transfer of training possible with the available technology.

Detailed discussion of the attributes of image generators and displays is a major theme of this report and the reader is directed to chapters 4 & 5, where more details are provided.

2.2.2 Tactile Cues

Tactile cues are derived from the feel of cockpit controls, switches and the like and need to be accurately represented so that cockpit procedures developed in the simulator will transfer to the real world. The importance of these cues is dependant on the nature of the aircraft system represented. Control feel and response is the most important as it directly influences the crew's ability to fly the aircraft. The force characteristics representing reversionary modes or those that represent system malfunctions are particularly important as the Mission Simulator may afford the only opportunity for the crew to experience such situations.

2.2.3 Motion Cues

Representation of the manoeuvring sensations found during flight is provided by motion systems in the Mission Simulator environment. As the simulator never leaves the ground, motion systems must attempt to represent sustained motion cues by illusion. Although none of the motion system techniques described below can provide the true sensation of flight motion, each can provide some benefits to the overall cuing environment of the Mission Simulator. A more extended discussion is given in section 4 of chapter 4.

2.2.3.1 Six Degree of Freedom Motion Platform

A six degree of freedom motion system represents an industry standard in motion simulation. As the name implies, it is a platform, mounted on 6 hydraulic jacks, which is capable of motion in pitch, roll and yaw and surge, sway and heave. As the jacks have limited travel, various filtering and limiting techniques are employed to derive maximum cuing value from a system which can never attempt to replicate real flight. In one of the techniques commonly adopted, the sensation of forward acceleration, for example, is provided by the motion platform initially moving forward to provide an acceleration onset cue and then sustaining that cue by tilting the cockpit rearwards. To the pilot in the cockpit the visual scene remains horizontal as the aircraft accelerates. A similar technique is used to represent aircraft lateral acceleration. Motion platforms of this type also provide good simulation of such special effects as the buffet associated with flight through turbulent air, the deployment of flaps or speed brakes, or the buffet associated with stall.

2.2.3.2 Dynamic Seats

Sustained g-force cues are not well represented by motion platforms. For this type of cue Mission Simulators typically use a g-seat/g-suit combination, together with visual system effects such as providing the illusion of tunnel vision and dimming the visual scene and cockpit lights during sustained high g manoeuvres. A g-seat is an aircraft seat with an inflatable seat cushion and back and a variable tension lap strap. Representation of positive g is provided by deflating the cushion and tightening the lap strap, negative g by inflating the cushion and loosening the lap strap. In combination with a g-suit, which works as it does in the aircraft, ie, inflates as positive g is applied, this system provides an effective cue as to the g being pulled, though not the same sensation as found in the actual aircraft.

Seat shakers are also sometimes used to provide motion cues, most often for the simulation of buffet or the vibration associated with rotary wing aircraft.

2.2.4 Audio Cues

Audio cues simulate cockpit sounds such as engine noise, airflow noise, gear retraction noises, and audible weapons sounds. The audio environment also involves the simulation of voice communications through the aircrew headsets, aural cues such as radio tones and call signs, audible warning and caution tones and weapons cues such as IR missiles search, track and lock-on tones. Audio cues contribute significantly to pilot situational awareness in the actual aircraft and, in the Mission Simulator environment, re-enforce visual and motion cues when properly synchronized.

To support the simulation of aircraft sounds, Mission Simulators usually employ multi-channel audio systems capable of providing spatially correct sounds with very high fidelity. Simulation of characteristic engine sounds, for example, involves matching both the broadband envelope and the narrow-band (tonal) characteristics of the noise spectrum over the full range of operating conditions.

2.3 Databases and Libraries

To support the simulation models and the creation of training scenarios, Mission Simulators typically incorporate a variety of user-controlled databases that contain data for the own-vehicle, the characteristics of the other simulated players in the training environment and the characteristics of the geographical and atmospheric environments. Chapter 5 reviews these databases in detail. Some of the issues are introduced here. While an optimum solution is to collect and manage this data in one system to ensure correlation of all information, this has not been the norm in the past. MIL-STD-1821 (see SIF, 1993) defines characteristics for the creation of a collective database which will provide correlated source data able to be used on different training devices. This standard is aimed at providing correlated source data which can be used to support the creation of visual and sensor databases. There are also systems now available commercially which create and manage data on player characteristics and tactics to be used during simulated missions.

2.3.1 Own-Vehicle Databases

Databases used to support the simulation of the own-vehicle contain data on the available stores-carrying options available for the aircraft. Typically there are many available combinations possible and such databases allow these simulated combinations to be kept up-to-date with the aircraft. The characteristics of the weapon can also be included in such a database, for example, the mass, drag coefficient and damage radius of a free fall bomb. This data is used by the simulation software to compute the weapon ballistics and score the aircrew's performance when using it.

2.3.2 Player Databases

Increasingly the simulation models that create other players in a tactical training scenario, ie, opposing and friendly forces, are supported by user-defined databases. In their most sophisticated form these tactical databases define all the player characteristics, from dimensions to sensors to weapons systems. Databases are typically arranged so that sensors and weapons are in separate libraries so that they can be selected and added to a platform characteristic to create the complete player. This attribute is particularly useful when defining complex players such as a warship. The weapon system libraries are designed to support the fidelity of modelling provided for the weapon. As computer performance has improved, this fidelity now approaches the fidelity of modelling provided for the own aircraft systems with a corresponding increase in the data stored in the respective database.

The visual appearance of the simulated players is generally defined in the image generator (IG) database. Available IG performance does not allow unlimited display of moving targets, as they consume IG performance reserved for generation of geographic features. Visual models of player vehicles are generally created in several levels of detail. Thus a tank may be represented as a simple box when viewed at long range, with more complex models being substituted as range is reduced.

The most advanced tactical simulation environments provide for a significant degree of automatic player interaction with the own aircraft, and even with other simulated players in any given scenario. To support this capability the databases contain libraries where player responses and doctrines can be entered. When conditions in the simulated scenario match a database case, an automated response is triggered, giving the simulated player a reaction capability consistent with the expected real world tactics. Such responses and doctrine libraries can be used, for example, to support decision making in air combat manoeuvres.

For aircraft mission simulation the electronic environment has a great impact on the tactics employed, thus player databases typically provide detailed radar system characteristics to allow the building of players which represent SAMs, AAA and airborne radar systems. Actual aircraft Electronic Support Measures (ESM) or RWR systems are often used in the Mission Simulator together with the actual aircraft operational software. This necessitates highly accurate radar system modelling to ensure the simulator response fully represents the system in the aircraft. These EW databases are, as a result, highly classified, which affects availability.

2.3.3 Geographic and Cultural Databases

The quality of the visual scene has the greatest impact on the ability of the Mission Simulator to provide training of the real aircraft mission and the database has a significant impact on that scene quality. The correlation of this database with that used by the sensor simulations such as radar is vital to effective training. In the creation of geographic and cultural databases, the aim is to maximize the realism and cuing capability of the visual- or sensor-provided scene without overloading the image generator and DRLMS. Databases are discussed further in chapter 5.

2.3.4 Environmental Database

Simulation of the prevailing weather conditions is an important aspect of the overall environmental simulation, and needs to provide for variations in these conditions over the gaming area and with the passage of time. A given scenario will specify a time of day and year when the simulated mission would take place together with the weather conditions which would prevail. Thus the weather conditions become part of the database defining that scenario. More detailed discussion is given in chapter 5. Simulator mission briefings include the expected weather en-route and over target as appropriate.

During the mission, the scenario environmental database parameters are used to control the visual scene, eg brightness, visibility, appearance of clouds and storms, as well as to provide the appropriate inputs to the flight model, eg wind speed, turbulence.

2.4 Operating environment

The product of the simulation models and the database elements discussed in the preceding sections is a simulated environment which will represent as closely as possible the real environment and allow the aircrew to interact in a realistic manner with that environment. A simulated mission can then be treated in the same manner as a real mission, except that the instructor has a means to control events and monitor crew performance.

The current state of the art in mission simulation can provide training scenarios involving friendly and opposing forces interacting with the own aircraft in a highly realistic manner. All aspects of the simulated environment can be fully integrated so that, for example, an opposing aircraft will exhibit consistent use of manoeuvres, sensors and weapons during an engagement which reflect intelligence as to expected tactics. The visual, radar and RWR indications provided to the trainee in the own aircraft will all be correlated. Other players such as AWACS or Ground-Controlled Intercept (GCI) can be provided to give tactical direction and supporting forces can be represented such as fighter cover for a bombing mission. The possible complexity of the scenario is limited only by the amount of processing power available in the computer system. As this available power continues to increase, more complex scenarios can be expected to be defined and trained for. The limiting factors may become the time and effort required to develop the scenarios as well as the availability of appropriate data.

A significant trend is towards the networking of training devices, of all types. This approach can provide a significant multiplier to the capability of a single machine as it can provide man-in-the-loop interaction with many players. There is a set of emerging standards for networking called Distributed Interactive Simulation (see DIS, 1993 and IEEE, 1995). Trials have demonstrated the feasibility of both local and long haul networks using such standards, but much research and development is still required.

3 SIMULATOR MANAGEMENT

Simulator management involves several activities and a number of different systems. The training mission itself must be controlled and monitored by some form of instructor station and training mission brief and debrief is typically performed from a brief/debrief station. Database workstations are used off-line to maintain the various databases accessed during a training mission.

3.1 Instructor Station

The instructor station is used to control and monitor the

execution of a training mission or session. It is typically a console fitted with a number of displays and controls to allow one or more instructors to supervise a simulated flight. Controls can consist of direct action buttons for often repeated functions such as simulator freeze, motion system actuation and, increasingly nowadays, re-configurable controls such as Liquid Crystal Display panels which provide context-specific functions appropriate to the mode of operation of the simulator. Displays are typically colour CRTs which present information in text and/or graphic form to allow effective monitoring and control to take place. Modern systems make use of windowing techniques and context-specific displays to optimise the presentation of relevant information. In many cases the display itself accepts data entry via a built-in touch screen.

For tactical aircraft simulation this instructor station is most often separated from the simulator cab in an off-board location and thus significant attention is devoted to the replication at the instructor station of the cockpit status. This usually involves both actual hardware display repeaters along with graphically represented repeats using the CRT displays. A typical example is illustrated in figure 3-1.

The exact layout and functionality provided by the instructor station is heavily dependant on the mission being trained and the preference of the simulator users. Configurations, though broadly similar in intent, are rarely similar in detail. However, there are a number of fundamental functions which are always present. Means to control the simulator state is always provided, often with direct action buttons. Means to monitor crew actions and the cockpit status is similarly always present, though the manner by which this is achieved can vary widely from device to device. Display formats and information also vary widely between systems. However the instructor is always able to control the execution of the tactical scenario, eg initiate and inhibit players, control weather. A tactical situation display which provides a plan view of all the players in the game is almost always available to aid in the instructional task, together with displays that indicate the performance of the trainees, such as a display to portray weapon impact points and release envelopes.

In a number of cases the instructor station incorporates controls to allow the instructor to represent other players in the environment. In their simplest form these controls allow the instructor to represent the communication traffic of other players. In a more sophisticated form an additional workstation is provided to allow the instructor to manoeuvre and control the systems of a player directly using controls such as a joystick and throttle and viewing a limited visual scene, thereby permitting participation as an air-combat adversary or a wingman, for example.

3.2 Brief/Debrief Stations

A separate station or stations is sometimes provided to allow crew briefing and debriefing to take place without interfering with the execution of training on the simulator proper. Usually such facilities represent subsets of the main instructor station in terms of available features and layout. They are designed, as the terms imply, to support crew briefing and debriefing. They are typically equipped with a graphics display system able to present the tactical situation to the trainees as the instructor sees fit.

Briefing stations often allow the aircrew to create tactical mission tapes for loading in the simulator mission computer, based on the simulator briefing session. Debriefing systems allow the instructor to play back data recorded during the mission to allow a critique of crew performance to be given.

3.3 Database Workstations

There are many possible variations associated with database workstations. The complexity and number of systems provided depends on the user philosophy with regard to simulator support. In general terms these facilities allow the simulator user to update and maintain the data associated with the visual system and sensor simulation systems, as well as maintain the various tactical databases associated with the creation of the training scenarios used in the simulator.

Visual database workstations typically represent the most extensive facility. A complete capability to support the development of new visual databases requires a powerful graphics workstation, together with data entry tablets and scanners to allow efficient entry of source data.

Radar workstations are similar in scope and can often be combined with visual system workstations. The need to share data between radar and visual to provide a correlated view of the world requires that the visual and radar system can exchange compatible database data.

Tactical database facilities can in fact be combined with the instructor or debrief station as they are typically accessing data which is stored on the simulator host computer system. However, these databases are often

sensitive in terms of data content (in a security sense) and many users prefer to control these data on a separate facility and only provide the data on a controlled basis to the operational simulator site. This type of situation is often found when there are multiple simulator sites for the same aircraft. Here the facility requires a computer system with the necessary man-machine interface to support efficient creation and editing of the tactical databases used to support the simulator scenarios.

4 EXAMPLES OF MISSION SIMULATORS

The remaining sections of this chapter briefly summarize the characteristics of the two mission simulators which have provided the knowledge and experience on which this report is based. These are the German Tornado Low Level Test Bed Simulator or VTS - Versuchstraeger Tornado Simulator (Morris and van Hemel, 1992), intended for the evaluation of simulation capability for low level flight training, and the UK Harrier GR Mk5/7, an operational mission training simulator (Clifford and Jackson, 1992).

4.1 Tornado Low Level Test Bed Simulator

4.1.1 Programme Origins

German and NATO air forces have long used German airspace to train for potential conflict. Much of the training was carried out at low level in German airspace and was restricted by the German government due to environmental considerations. During the course of the Tornado Low Level Test Bed Simulator programme, this restriction was extended to prevent any flying below 300 meters (1000 ft) above ground level.

Faced with the need to maintain Tornado aircrew readiness despite a fundamental restriction in the flying training possible, the German Forces chose to determine to what extent simulator training could bridge the gap and allow flying time to be optimized. It was recognized that the seven operational flight and tactics simulators (OFTSs) fielded for the Tornado, while effective, had limitations in their capability and could not be used "as is" to provide the required training supplement.

CAE Electronics GmbH, supported by CAE Electronics Ltd, provided the Tornado Low Level Test Bed Simulator to allow an evaluation of the new visual technology to be performed by the German Forces. The programme started in June 1989 and the completed test bed was offered to the German Forces, for their 6-month evaluation, in June 1991. The technology which provided the basis for CAE's proposal was the Fibre-Optic Helmet Mounted Display (FOHMD). Use of the FOHMD allowed both Tornado crew members to look in any direction, independent of the other, and be provided with an appropriate view of the outside world scene, while still maintaining the correct cockpit relationship. It also allowed the fitting of a six-degree of freedom motion platform and respected the spatial limitations imposed by the existing simulator installations.

While current funding constraints have delayed the original objective of upgrading the seven in-service Tornado OFTSs with the new technology applied on the Test Bed Simulator, the programme and, in particular, the 6-month evaluation of the system by the German Forces, has yielded a wealth of valuable data (van Hemel, 1992 and Foldenauer, 1992) on the use of simulation to support low level flight operations.

4.1.2 Overview of Simulator

The Tornado Low Level Test Bed Simulator, or VTS (Versuchstraeger Tornado Simulator) as it was designated by the German Forces, had as its design baseline the existing OFTS Tornado simulators. To this baseline was added a 6 degrees-of-freedom motion system, dual FOHMD display systems and an Evans and Sutherland ESIG-1000 image generator. Much of the computer linkage and instructor station equipment was taken from an existing Flight Simulator Development Rig (FSDR) at the CAE GmbH facility in Stolberg which was designed to support development activities for the seven in-service OFTSs. The FSDR was mated with a new Tornado simulator cockpit and computer system.

The cockpit design was based on that of the in-service OFTSs, but with an extended platform to support the installation of the FOHMD optics modules. The platform was reinforced to allow use on the 6 degrees-of-freedom motion system and the g-seat/g-suit system from the OFTS was installed. Changes to the software were made to allow combined or separate use of the g-seat/g-suit and motion systems.

The OFTS computer system was replaced with four Calder computers which are compatible with the original TI-980, but run considerably faster. The flight model was updated to run at 60 Hz in the air, and 20 Hz on the ground. Three VAX-3800 computers were added to provide for the computational requirements

and interface for the FOHMD, IG, motion system, and wingman.

A visual system was provided on the OFTSs for the pilot only. The VTS, however, uses two FOHMDs to provide wide field of view images to both the pilot and Weapon System Operator (WSO). The FOHMD makes use of two General Electric light valve projectors for each eye, the optics being configured to provide an eye-slaved high resolution inset within a large, lower resolution background. The FOHMDs are driven by the ESIG-1000 image generator which provides three visual channels to each helmet (the left and right eye insets are driven by a common channel), and an instructor operator station (IOS) channel.

The major components of the VTS are shown in figure 3-2.

4.1.3 Visual System

The FOHMDs used on the VTS provide each crew member with an instantaneous field of view of 127 degrees by 66 degrees, aligned with the wearer's head position, to achieve a total field of regard capability which is essentially unlimited within the constraints of the cockpit visibility envelope. An eye-tracked area of interest is provided within this total field which provides an area of 25 degrees by 19 degrees. Figure 3-3 illustrates these fields of view. The resolution of the background field is 5 arc minutes per pixel and that of the inset 1.5 arc minutes per pixel. Scene brightness was up to 50 ft-lamberts and contrast ratio greater than 50 to 1.

The image generation is provided by the ESIG-1000 system giving seven channels of output, three for each crew member and one as an instructor repeater. Each crew member is provided with a background channel for each eye of 1 million pixels and 1200 polygon capacity and an inset channel of 1 million pixel and 2000 polygon capacity shared between both eyes. Figure 3-4 illustrates the image generation and optical system for each crew member.

4.1.4 Systems Simulation

The VTS was designed to support a specific visual evaluation and therefore did not include all the elements of the in-service OFTSs. The most notable missing element was simulation of the EW system and external EW environment. The aircraft mission computer was included in the system due to its principal role in the navigation and weapons delivery capability of the aircraft. A DRLMS system was borrowed from an in-service OFTS as this item was also considered to be essential to the aircraft mission capability. Indeed, all systems which could have had an impact on aircraft handling or weapons delivery were fully represented in the simulator.

Most of the systems simulation models were taken 'as is' from the in-service OFTSs. Some were modified or extended to take advantage of the higher performance IG available, such as the weapons simulation which was extended to include weapons fly-out effects and detonations. A notable additional model was the computer-controlled wingman model, which was added to allow the assessment of formation flying of various kinds, ranging from battle formation at extended ranges to close formation flying.

4.1.5 Flight Handling and Performance

The in-service OFTS represented late 70s to early 80s technology and utilised a flight model which ran at a relatively low frame rate. This was felt to be unsatisfactory for the VTS and so the flight model was enhanced to run at 60 Hz. With these changes the time from control action to completion of visual scene update was less than 120ms, of which 72ms was attributable to IG computation and display time.

4.1.6 Motion Simulation

The VTS incorporates both a 6 degrees-of-freedom motion platform and a g-seat/g-suit for each crew member. As part of the evaluation process, the simulator is designed to operate with or without the motion platform. The contribution of the g-seat/g-suit can, therefore, be adjusted, dependant on whether the motion system is on or off, to optimize the available cues. Included in the motion simulation effects are g-dimming and tunnel vision effects on the visual display.

4.2 The Royal Air Force Harrier GR Mk5/7 Mission Simulators

4.2.1 The Aircraft

The Harrier GR Mk5/7 aircraft have a primary role in low level offensive support, operating at speeds in excess of 500 knots at low altitude, over undulating terrain, by day and night and under all weather conditions. Tasks are performed under manual control using visual references only. Visual references are enhanced in low light conditions by the use of FLIR and NVGs. There is currently no two-seat training

version of this aircraft.

4.2.2 Overview of Simulator

Two simulators were designed to meet the staff requirement of the UK Royal Air Force as specified in 1985. Link-Miles Ltd (now Thomson Training and Simulation Ltd) was the prime contractor for the design and build of the core simulator and its integration with the Singer-Link (subsequently CAE-Link) visual system. The requirements called for mission simulators capable of providing the full spectrum of VSTOL operational flying training, together with means of controlling and evaluating aircrew performance within flexible wartime scenarios, including NBC and EW conditions. Environmental issues served to emphasize the desirability of seeking technological solutions to providing operational training synthetically.

The principal hardware components comprise a cockpit assembly, including projection and electronic interface equipment, mounted on a 6 degrees-of-freedom hydraulic motion system surmounted by a 24 feet diameter visual display dome. Off-board equipment includes a two-position Instructor Operator Station (IOS), a Remote Debriefing Facility (RDF) and a Visual Database Workstation (DBWS). These, together with the computer and image generator peripheral equipment are housed in a re-locatable building complex.

4.2.3 The Visual System

The field of view is +80 degrees in elevation, -50 degrees in depression and ± 120 degrees in azimuth. To provide the required resolution at an affordable cost, an Area-of-Interest display is provided using the CAE-Link Eye Slaved Projected Raster Inset Technology (ESPRIT) system. ESPRIT provides an eye-tracked, high resolution, circular area of interest, nominally 16 degrees in diameter, which is merged into a fixed background scene of lower resolution. The nominal resolution is 1.7 arc minutes per pixel for the inset and 9-15 arc minutes per pixel for the background.

The visual system imagery is provided by the CAE-Link Modular Digital Image Generator (MODDIG). As well as driving the ESPRIT display, it provides the means to simulate the Angle Rate Bombing System and the FLIR system. MODDIG represents the technology of the mid-1980s and does not include the use of phototexture. It provides a comprehensive range of visual effects, including air to ground, air to air, SAM and AAA weapon effects and correctly correlated dynamic ground, air and maritime targets.

A suite of database generation tools is provided to allow amendments of existing databases as well as the generation of new databases and models.

4.2.4 Avionics and Weapons Management

Fidelity of avionics system simulation is optimised by use of actual aircraft or simulated systems, controlled by the Mission Computer, which is 'as aircraft'. Unmodified aircraft Operational Flight Programs are loaded into the Mission Computer. The Head-Up-Display is modified optically to enable the displayed symbology to appear coincident with the visual dome display surface. The Electronic Warfare and Weapons Management systems are fully simulated.

4.2.5 Flight Handling and Performance

The simulator provides a correctly synchronised range of environmental and pilot initiated cues. On-set motion cues are provided by the motion platform; these cues are perpetuated by the g-seat/g-suit system. The cockpit lighting and visual scene also react to G forces; as sustained G forces are simulated, the visual scene collapses progressively to provide a "tunnel vision" effect and brightness levels dim.

Low latency has been achieved in the simulator, with response times in the order of 130ms from control input to visual system update.

4.2.6 Instructor Operator Station

The training sorties and pilot activities are planned, controlled and monitored at the Instructor Operator Station (IOS). The IOS provides facilities for a flight simulator instructor and an aircrew instructor but can be operated by a single instructor if required. A tactics development facility is available at the IOS to allow the off-line generation of tactical scenarios. Other IOS facilities include 30 minutes of record/replay, weapon scoring and freeze/reset.

4.2.7 Remote Debrief Facility

All major elements of a sortie are recorded and may be replayed for analysis/debrief at the Remote Debrief Facility (RDF). This facility includes a monitor to give a repeat of the pilots visual forward field of view. The facility can be used to view own-ship line-of-sight from another point of view, such as from a ground threat point of view as own-ship transits the tactical scenario.

4.2.8 Night Attack Training

The GR Mk5 simulator reflects the fact that this aircraft's night attack capability is limited to the use of NVGs. The GR Mk7 version of the simulator, however, represents the aircraft's extended night attack capability and includes FLIR system simulation. Both simulators will eventually be to GR Mk7 standard.

5 CONCLUSIONS

Mission simulation requires that the whole aircraft, its weapons and systems be entirely represented as well as the external environment facing the aircraft during a simulated mission. The intent is to immerse the aircrew trainees in as authentic an environment as can be achieved, with as many real world-like interactions as possible. As a result, a mission simulator is arguably a more complex device than the aircraft that it seeks to represent.

Fig 3-1 A typical example of an off-board Instructor Operator Station (Harrier GR Mk 5/7)

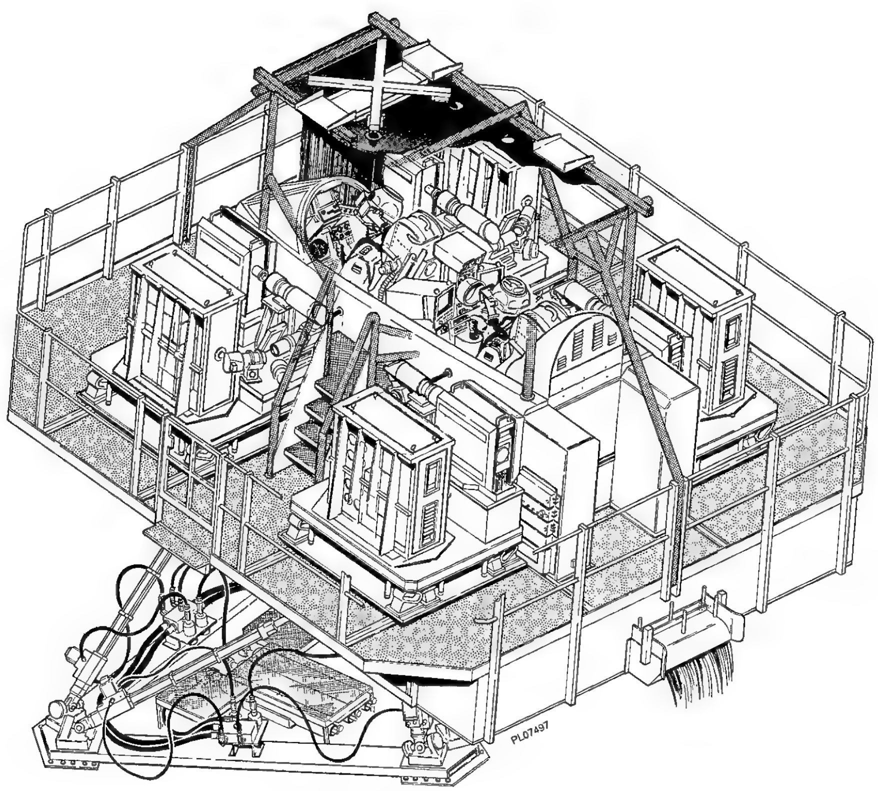

Fig 3-2 The major components of the Tornado Low Level Test Bed Simulator

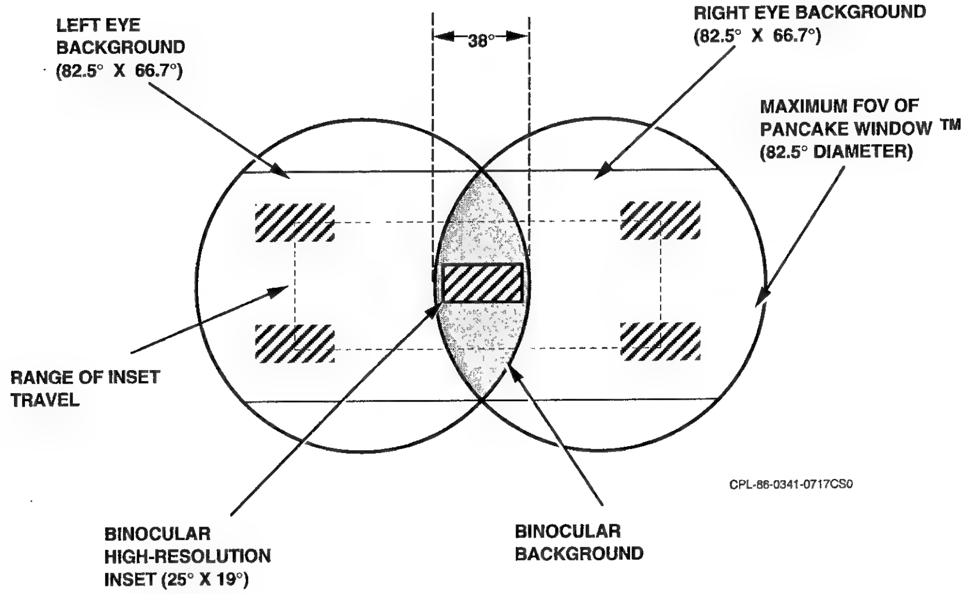

Fig 3-3 Tornado Low Level Test Bed Simulator - fields of view

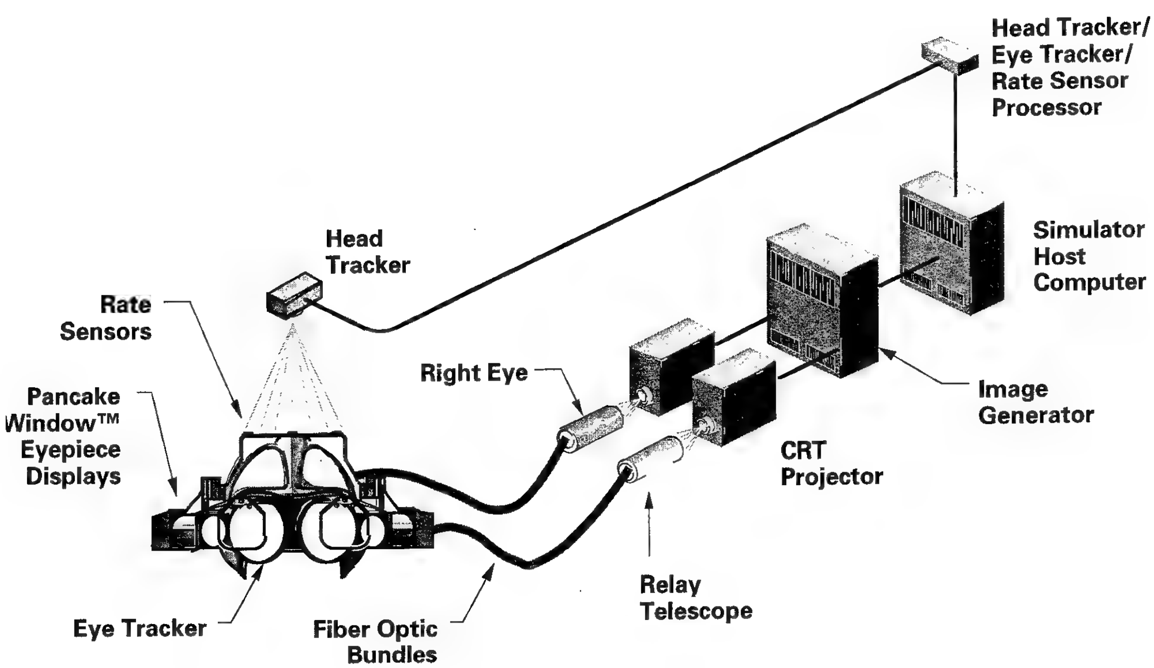

Fig 3-4 Tornado Low Level Test Bed Simulator - image generation and optical system for each crew member

CHAPTER 4

PILOT CUEING ENVIRONMENT

CONTENTS

1 INTRODUCTION

1.1 Summary

The human pilot receives stimuli through a number of senses: sight, sound, touch and motion (vestibular, tactile, proprioceptive and kinaesthetic). An effective simulator needs to stimulate all these mechanisms where appropriate to the task. This chapter reviews how to provide the pilot with a comprehensive cueing environment, and discusses technology trends.

Section 2 considers the internal vehicle environment, or cockpit, and concludes that it is generally not difficult to replicate the form and appearance of the physical cockpit. Challenges do exist, however, in achieving appropriate fidelity in the feel of the primary controls and in reproducing sensor-based displays.

Section 3 examines the external, visual cueing environment. It reviews the visual display simulation technology used to support low level training in flight simulators for high speed combat aircraft and assesses the advantages and disadvantages of the various solutions by identifying the characteristics of the various options and comparing them to an ideal case. It concludes that area of interest display solutions offer the best available technology for the present and the medium term to satisfy the need to provide low level flight training in a synthetic training device. Research into the contribution of detailed and peripheral vision to the overall perception of the scene as perceived by the crew is required.

Section 4 discusses the motion cueing environment, how pilots sense and perceive motion and how the various simulator devices, principally motion platforms and dynamic seats, attempt to generate appropriate motion cues. Motion cueing is fundamentally different from all other aspects of cueing in flight simulators in that total fidelity with the external natural environment is not sought and can never be achieved. This is because the forces and accelerations generated in flight cannot be fully reproduced within the physical constraints of a ground-based device. Therefore some form of deliberate deception is necessary. Experience in the Tornado Low Level Test Bed programme showed that crews liked the presence of motion. The trend to deployable training devices needs research on compact forms of motion cueing device other than motion platforms.

The chapter draws heavily on the experience gained on the German Tornado Low Level Test Bed programme, as this programme has yielded the largest body of data to date on the subject of low level, high-speed flight simulation. The chapter is not only a review of the current technology but also of the direction development is expected to take and how that development may be influenced by the future requirements of the military.

1.2 Cueing and Perception

The human being detects external data through various sensory mechanisms (Boff, 1988) and changes such data, via the brain, into perceptions and information. Human sensing and perception are inextricably interwoven, and are also strongly influenced by knowledge and experience. The purpose of a simulator is to generate stimuli to provide cues which lead to a sufficient appreciation of what is happening in the pilot's environment.

The most challenging aspect of a full mission simulator is how to provide all the necessary external stimuli to the pilot's visual, hearing, vestibular, tactile, proprioceptive and kinaesthetic senses. Vision is the primary sense utilized by the pilot in controlling the aircraft. The pilot's perception of his surroundings is a key element in proper control of the aircraft. Once the pilot has assessed his situation, he can then use his other senses to make the necessary physical and mental adjustments.

For example, during low level flight, it is very important that continuous attention be directed to the horizon, as well as to particular objects on the ground and in the air. Around 90% of the pilot's attention is dedicated to the real-time view out of the cockpit. A simulator must provide the flight crew with a detailed visual representation of the external world. Low level flight at 250 ft (or less) above the ground demands high psychophysical efficiency from the crew. Visual concentration is very close to human limits. Object recognition depends on lighting, shading, background, contrast, time visible, and the physical characteristics of the object. During low level flight, it is common for the flight crew to encounter some adverse flight visibility conditions which degrade visual perception. For example, rapidly changing lighting levels within the cockpit strain the eye, which must constantly adapt to the changes in illumination, and in addition the wind screen is also often covered by dead insects, which obscure outside vision .

Positive and negative "g" force due to manoeuvres, plus vibrations and buffeting, make it uncomfortable for the pilot to read maps and look through the HUD. Such buffeting also causes difficulty in operating the many cockpit switches and the high angular speed severely limits the recognition of terrain objects. Safe and effective low level flight needs long and effective training to allow pilots and navigators to reach perfect individual concentration, precise target observation and recognition, good extrapolation from incomplete perceptions and familiarization with the terrain all around the cockpit.

The training effectiveness of a mission training or mission rehearsal device may be compromised if adequate cueing fidelity is not supplied, leading to aircrew having to adapt their behaviour to accommodate simulator deficiencies. For example, the visual scene content of the database will not exactly reproduce the real world, but only include representative elements and therefore aircrew must interpret the simulated scene. The subjective opinion of the fidelity and hence training effectiveness of simulators will be influenced by these

factors. To mitigate these affects it is essential that the cues that are provided are well matched and synchronized.

2 INTERNAL VEHICLE ENVIRONMENT

The internal vehicle environment provides the essential interfaces between the crew and the vehicle. It is generally not difficult to replicate the form and appearance of the physical cockpit. This must provide a seat or seats, and the primary flight controls (stick, pedals and engine levers). The feel of any force-loaded lever should be reproduced by a control loading system. Fidelity in this respect is often not as good as it might be. All appropriate buttons, dials and screen displays should be provided, with representative form and function. Sounds are important environmental and system cues, whether to indicate vehicle-related functions such as correct (or incorrect) operation of the primary power-plant, air flow noises, undercarriage or flap selection, or to provide warning cues of malfunctions or external hostile events.

The most challenging elements in simulating a modern internal vehicle environment are reproduction of sensor-based displays and how to simulate software-operated black boxes, such as mission computers. Simulation of sensor-based displays is discussed further in section 3 of this chapter and in chapter 5. The choice between simulation of complex avionic boxes and stimulation of real hardware is reviewed in chapter 7.

3 VISUAL CUEING ENVIRONMENT

3.1 Introduction

This section is concerned with how a visual image is presented to the trainee in the cockpit. It addresses the features of the image generator and the display system which are considered necessary to support low level flight. The characteristics of the visual image presented to the pilot are also strongly influenced by the database features described elsewhere in this report (chapter 5) and reference is made to these database issues where they have a particular impact on the resulting image.

For the purposes of definition, the image generator is described as that device which processes the database information in accordance with simulator dynamic parameters, such as viewpoint location and direction, in order to generate real-time image data for presentation on the display system. The display system is that device which uses the image generator output to produce the visual images observed by the simulator pilot.

The configuration for the two elements varies as a function of the training requirements of the simulator and of the funding available for the procurement of the visual system.

In the real world the visual image observed by the aircrew is characterised by:

a. Field of view limited only by the simulated aircraft structure.

b. Unlimited image detail.

c. Very high scene content.

d. Brightness levels ranging from night to full daylight under bright sunshine.

Producing a synthetic visual system which provides such performance characteristics is beyond the current and foreseeable state of the art. Fortunately, such attributes are not necessary **to achieve training effectiveness** as the human eye and brain combination filters much of the data presented in the real world scene, particularly when using the information to perform precision tasks such as low level, high speed flight (see AGARD (1981), section 5).

An ideal visual presentation system is one where the four characteristics discussed above are tailored to provide the necessary cues to allow the optimum performance to be achieved by the trainee aircrew. Optimum performance in this context consists of performing the simulator training mission in the same manner as an aircraft mission, with an equivalent crew workload and using the same cues as used in the real world, such that the simulator training provides positive training transfer to the aircraft case.

The following discussion is directed towards the visual display system requirements for a fast jet simulator and is based on the assumption that databases adequate to support the visual presentations described can be provided. Scene generation and database issues are discussed further in chapter 5.

3.2 Visual System Requirements

For a fast jet simulator, the display and associated image generator and database requirements will differ depending on whether the task is air-to-air combat

training or ground attack training. Thus, it is possible to provide visual presentations aimed at either role, if justified from a cost standpoint. However, as many aircraft are in fact multi-role and as ground attack missions could very well become air-to-air as a result of enemy air defence, it would be preferable to have a system suitable for both training tasks.

3.2.1 Air Combat

There are several key features of an air-to-air engagement which drive the visual presentation requirements. The opponent or opponents can be anywhere in the sky relative to their own aircraft, first detection is often the most important factor for survival and the ability to determine the opponent's manoeuvring is necessary to achieve a weapons firing solution. Thus for effective air-to-air combat training the visual requirement is for a wide field of view limited, ideally, only by simulated aircraft structure, and for high target resolution and detail, sufficient to detect and identify a target at realistic ranges and to determine target relative attitude and attitude changes during the course of an engagement. Air-to-air engagements may very often take place at low level which creates the additional requirement for reasonably detailed ground relief and features capable of providing motion cueing, particularly with respect to altitude changes. A more generic solution with simple representation of sky and earth can be acceptable if only dedicated air-to-air training is desired. Other requirements are for representations of missile launch and trajectory and gunfire from the opponents.

3.2.2 Ground Attack

The cues used during ground attack are somewhat different from the air-to-air case. Generally flight is much closer to the ground and thus the crew makes use of cues in the scene which allow for the estimation of altitude and airspeed as well as recognition of known landmarks and terrain features to aid the navigation task.

The significance attached to each cue type depends upon the task undertaken, the altitude flown and what features in a scene a particular pilot uses. The experimental studies performed on the German Tornado Low Level Test Bed (LLTB), as well as the crew surveys which were carried out before the testing began, have indicated that vertical features, such as trees, buildings and towers, as well as the perceived shape of the terrain, are used for altitude cueing. Airspeed cues are also provided by known objects streaming by in the periphery and are additionally provided by the texture flow as the ground is overflown. Navigation requires feature recognition relative to the data provided by aircrew maps, briefings and other comparisons to prior knowledge.

The Tornado programme has indicated that, during low level flight, pilot gaze is generally restricted to a relatively small region in front of the aircraft with limited attention given to other areas. However, navigational checks and high g manoeuvres, as well as formation flying, call for the pilot to scan areas well outside this region for adequate control.

Thus for ground attack and low level flight training, the visual display must present a highly detailed representation of the terrain contours and the features which are expected to populate it, with a field of view covering the forward area from the aircraft. The display resolution must be sufficient to recognise cues and react to them while they are at relatively long ranges, (the higher the airspeed the greater the range at which recognition is necessary) over the full field of view.

While low level flight commands crew attention in a relatively restricted area, manoeuvring to engage a target considerably extends the field of view required. In order to ensure target tracking during run-in, tight turns, pop-up and dive bombing manoeuvres, etc, the visual field of regard needs to be much larger, up to 180 degrees horizontally, and -60 to +90 degrees vertically, with limitations only due to aircraft structure.

U.S Air Force studies (Barrette et al, 1990) carried out at the Human Resources Laboratory (HRL) at Williams Air Force Base have attempted to gauge the effect on aircrew performance of the instantaneous visual system field of view. As a result of these studies the generally accepted, instantaneous, field of view requirement, necessary fully to support all aircrew operations in a simulator, is a minimum of 120 degrees horizontally by 60 degrees vertically (these figures are total, not plus and minus). These field of view studies were performed with area of interest display systems in which the field of regard can be much larger than the instantaneous field of view, so they do not provide a total answer. However the HRL data have been generally incorporated into the characteristics of systems deployed to date.

3.2.3 Accuracy

In currently fielded aircraft, the HUD provides the aircrew with the principal reference with which visual

system accuracy and correlation with other sensors can be judged. The visual system accuracy and distortion characteristics must, therefore, be optimized in the area covered by the aircraft head-up display, in order that the visual target will correlate properly with the tracking data presented on that display. Future weapons and sensor technology, allowing for off-axis aiming of weapons and possibly incorporating helmet-mounted sighting systems, will extend the display accuracy requirement to cover the whole field of view. Research is required to ensure that the Image Generator (IG) and display system combination are capable of meeting these accuracy requirements.

3.3 Visual system performance

3.3.1 General

The following sub-sections discuss the various performance characteristics required to meet the visual systems requirements defined in section 3.2 above. The performance described is that which is currently available or will be available in the near term. Much of the performance data discussed and observations made are derived from AGARD (1981), which defines the key parameters used to quantify visual system performance. It concludes that the performance of the visual system is dependant on a number of fundamental characteristics of the image generator and display which are, more often than not, inter-related. Thus, for example, a discussion of resolution must include consideration of brightness and contrast as they fundamentally affect the perceived resolution.

A visual display system is composed of one or more display units, each unit consisting of an imaging device (projector or CRT), which is driven by an image generator channel, and associated optics. The optics, consisting of various combinations of lenses, mirrors, beam splitters and screens, produces a real or virtual image of the picture presented on the imaging device. This final image, which covers a defined angular field of view at the pilot's eye, is what the pilot perceives as a result of the whole visual process. The characteristics of the result can be defined, essentially, in terms of the field of view, resolution, brightness and contrast ratio of the display elements.

The scene content is more difficult to quantify, especially with the texture capabilities present in current image generators. For low level flight the Tornado LLTB experience has indicated that three dimensional scene elements are of significant value and their presence in the scene is fundamentally determined by the face or polygon processing capacity of the image generator. Use of area of interest solutions can significantly affect the required capacity and thus requires special consideration. For example, the balance between scene content in the inset and background regions of an area of interest system (see Section 3.3.4) can impact the number of polygons required in each region.

3.3.2 Field of View and Resolution

These parameters are discussed together as they are fundamentally interrelated. The resolution of a given number of image generator pixels is dependant upon the field of view over which they are displayed. AGARD (1981), section 3.4.2, discusses the manner in which the perceived resolution is also affected by the overall Modulation Transfer Function (MTF) of the display elements. The system MTF implies that, even though the IG may provide an output of 1 million pixels, or more, the display chain effectively filters the image due to the performance limitations of each element. Display resolution is typically measured at an MTF of 10% , ie the difference in brightness between light and dark pixels on the display is 10%.

The limiting resolution of the eye is something less than 1 arc minute in bright daylight conditions, though this resolution deteriorates at low light levels. AGARD (1981), section 3.4.1, contains curves of the nominal eye visual acuity. Above a brightness of approximately 10 ft-Lamberts, the eye's acuity varies little. Thus, for the observer to benefit from a high resolution in the displayed image it should, ideally, exceed this brightness level. (Conversely, it can be argued that night scenes can be provided at much lower resolution and still provide a satisfactory result.)

Assuming an overall MTF of 70%, a conservative figure, an image generator producing 1 million pixels can support eye limiting resolution, for a daylight scene, over approximately 15 degrees circular field of view. The field of view requirements discussed in section 3.2 above are considerably larger than 15 degrees and thus many visual channels (30 or more) would be necessary to support a scene providing eye-limiting resolution over the whole visual surface.

The resolving capability of the eye is not uniform over its field of view. Rather, high resolution is achieved over a relatively small area concentrated on the fovea, with resolving capability falling off rapidly with increasing angular offset from this area (see AGARD (1981), section 3.4.1). Many current visual system

designs take advantage of this characteristic, as a means to reduce the number of channels of visual display required to create the illusion of a high resolution scene.

3.3.3 Fixed Display Units.

A common approach to visual display systems is to provide a number of fixed display units, located to cover the desired field of view. The unit field of view is selected on the basis of dimensional considerations and the provision of adequate resolution (typically ranging from 30 x 40 degrees to 40 x 60 degrees for a single display unit). Three or four such units can then yield a total field of view of up to 180 degrees horizontally and 60 degrees vertically, depending on orientation and cockpit/windshield geometry. Various methods are used to provide the display, ranging from direct view screens to continuous mirror, virtual image systems. For the single-seat fast-jet application, considered here, the displays are either mirror/beam-splitter types, (and furthermore may be either pupil-forming or non pupil-forming) or direct view systems, usually projected on the inner surface of a dome.

Achieving wide fields of view with such techniques is difficult as it requires large numbers of channels and can often not be managed within the space available. Projected systems can also be compromised, when a dome is used as the projection surface, by the spherical integration of the light over the surface of the display. This phenomenon can reduce the contrast of the viewed image to very low levels.

3.3.4 Area of Interest

Area of interest (AOI) refers to the technique employed to take advantage of the eye characteristic described in section 3.3.2 above. Only those areas of the scene where the aircrew's attention is focused are rendered in high resolution. The rest of the scene is provided at much lower resolution, thereby reducing the performance and channel requirements for the overall system. Area of interest displays are currently being widely applied to address tactical flight training problems and represent the state of the art in display system technology. Most major visual system suppliers now have or are considering such systems and the two currently fielded systems aimed at low level flight simulation, the Tornado LLTB in Germany and the Harrier GR Mk5/7 in the UK, both use variations of the area of interest solution.

Area of interest systems can be divided into two categories, those which are target-driven and those which are pilot-gaze driven. These will now be discussed.

3.3.4.1 Target-Driven

Target-driven area of interest systems are widely used for tactical aircraft pilot training, typically as air combat dome systems. This method is suitable for air-to-air combat simulation, where the target (or targets) represents the only possible area of interest. A target display unit need only cover an angular field of view of 10 to 15 degrees (as a 30 metre target at 300 metres range subtends an angle of approximately 6 degrees) and therefore can achieve close to the ideal resolution. A display unit, slaved to the relative own-aircraft-to-target direction is required for each target, and takes the form of one or two projectors providing the target image on the inside surface of a dome. When the target image is provided by laser or TV projection of an actual model, resolutions can indeed match the capability of the human eye. However, long range detection of the target is improved by the unrealistic halo that often surrounds the target image due to the iris of the projection system. Target classification is often difficult in such systems due to the poor contrast of the image and the low overall brightness of the display. Laser projectors can improve target brightness and contrast and can provide very high resolution. Also in such systems two projectors are necessary to achieve full 360 degrees coverage with no blanked areas. These are generally monochrome projectors for optimum brightness and contrast.

Such display solutions are less well suited for air-to-ground applications, where targets may be widespread. Typically, a low resolution background is provided using fixed wide-angle projectors. The resolution of such a background is typically much worse than 1 arc minute per pixel, and is usually similar to that provided to the commercial airline user in wide angle displays.

3.3.4.2 Line of Sight Driven

As target-driven display solutions are not suitable for air-to-ground applications due to the generally poor resolution of the ground displayed to the pilot, attention has focused on systems where the display is slaved to the pilot's direction of regard, or line of sight. This method uses head and, in several instances, eye position sensors to determine the pilot's line of sight. A visual display unit then produces a small (20 x 25 degrees) high resolution area (approximately 1.5 arc minutes per pixel) centred on this line of sight.

A background image of lower resolution may be provided either from fixed display units covering the total required field of view or by a wide field of view (e.g. 67 x 130 degrees) display unit slaved in synchronism with the high resolution unit. The combination of inset and background images produces a perceived field of view of apparently uniform resolution equal to the resolution of the inset, throughout the field of view covered by the moving images.

The line of sight driven system takes one of two forms:

1. A projected system where the high resolution (and low resolution, if applicable) projector is servo-driven in accordance with the head and eye position sensors. The image is projected on a spherical dome or dome segment. There are both head-slaved and head- and eye-slaved dome projection systems currently available. The Harrier GR5/7 simulator (Clifford and Jackson, 1992) is the only example of a head- and eye-slaved system.

2. A helmet-mounted system, where optical components of the display units are mounted on the pilot's helmet and thus automatically follow head motion. The high resolution inset may be fixed or eye-slaved within the lower resolution area. In this case, separate images must be generated for each eye. At present, the Fibre Optic Helmet Mounted Display (FOHMD) represents the only example of an in-service helmet mounted system (Morris and van Hemel, 1992). This solution is employed in the Tornado LLTB.

3.4 Image Generator Performance

3.4.1 General

The performance of the image generator (IG) has a significant impact on the overall visual result presented to the aircrew as it determines the scene content. A high scene content is necessary to support flight at low level to provide height, airspeed and navigation cues to the aircrew. At the present time the only documented study of simulation in this regime is that provided by the German Tornado programme. The results of this work (Morris and van Hemel, 1992; van Hemel et al, 1992) indicate that the scene should contain significant numbers of three dimensional objects, such as trees and buildings, as well as high frequency texture information and well defined terrain contours. These requirements imply image generation systems capable of providing large numbers of faces or polygons per channel as well as full colour textures.

Systems are available in the marketplace today which are able to provide such performance, though careful matching of IG performance with the intended display solution is necessary to achieve acceptable results.

3.4.2 Impact of Display Solution

Fixed display solutions provide no special problem for the IG, as each channel performance is the same to provide uniformly distributed information throughout the scene. Area of interest solutions, however, require that the performance of each IG channel be optimised according to its contribution to the scene perceived by the aircrew. The degree of `specialization' of the IG channel is dependant on whether the visual system is target-driven, or line-of-sight driven.

Target-driven systems represent a special case as the target projector is only required to provide an image of the target, thus the task for the associated IG channel is straightforward. The background scene, if provided by an IG, is essentially the same as a fixed display system.

The performance of the IG channels for line of sight driven systems depends further on whether the system is eye-slaved or merely head-slaved. Head-slaved systems, by definition, allow the visual system observer to scan the whole displayed area and, in particular, recognise any boundaries which may exist between the high resolution channel and the background channel or channels. (This assumes, of course, a high resolution inset. For uniform channel resolution there is no special tailoring required.) Eye-slaved systems attempt to position the inset, high resolution, channel to track the observer's direction of gaze. Thus background channels can be treated somewhat differently as they are not directly viewed but instead provide for peripheral vision.

With head-slaved systems the IG performance must pay special attention to the prevention of anomalies at the boundary between the high and low resolution areas. Objects must be visible continuously across the boundary and should not change size or intensity. Light points present a particular problem, unless there is the ability to change their size between inset and background. Thus a two pixel light point in the background may require to be modelled as eight pixels in the inset for adequate size matching. The ability to display calligraphic light points in both background and inset could go some way towards offsetting this problem. Even with this approach, however, field of

view differences require light point brightness differences. To achieve the same density of scene elements in the background channel as the inset may well require a larger number of polygons be displayed in the background channels. The problem is further complicated by the level of detail management scheme supported by the IG as well as the relative resolution of each displayed pixel and the load management technique applied.

Eye-slaved systems must further consider the physiological characteristics of the human visual system, in order to determine what level of contribution the inset and background make to the observer's perception of the scene. AGARD (1981) provides some indications of the types of effects that need to be considered. Scene elements popping into view at the boundary must still be controlled. However, the addition of significant detail to the scene element, such as windows on a house, is a way to maximise the scene content. Similarly texture cues in the periphery and moving objects are features which should be present in the background scene. Indeed, it may be that features such as moving objects need to be enhanced to ensure that they get observer attention, as they would in the real world.

3.4.3 Impact of Database

The discussion above addresses how IG performance needs to be matched to the selected display solution. The characteristics of the database also have a significant impact on the perception of the scene. Essentially the database must support the scene content by providing models of sufficient detail to satisfy the resolution available in the inset channel, at the closest expected range, as well as enough levels of detail in those models to allow smooth transition to the background channel without creating an unmanageable polygon load on the IG hardware. Elements of the database, such as light points, may require channel-specific models to support these goals.

An additional consideration for the database is the need to enhance the target models to support visual acquisition and recognition at real world-like ranges in the trainer. Depending on the display solution applied, this may require either size adjustment, contrast adjustment, or both, to achieve acceptable results in the final visual system.

Further discussion of databases is contained in chapter 5.

3.5 Display system selection

3.5.1 General

On the basis of the requirements outlined in section 3.2 and the performance discussion in section 3.3 above, the most viable choice today for a display system for a fast jet aircraft simulator appears to be an area of interest system. For the medium term (5 years or so) this conclusion would still seem to be true, with the likelihood that the user would be afforded more choice. The following review outlines the general characteristics of the area of interest systems currently available, compares them with the 'ideal' features identified in section 3.1, indicates their applicability and discusses their relative advantages and disadvantages.

It should be noted that the discussion provided below is heavily influenced by the information provided by the German Tornado programme (Morris and van Hemel, 1992; van Hemel et al, 1992), the only such programme specifically aimed at gathering objective data to determine the relative merits of simulation for low level flight training tasks. Objective data of this nature has not yet been made available on the other systems discussed below (although target-driven systems represent a well-known technology).

3.5.2 Target-Driven System

3.5.2.1 General characteristics

The most common application of a target-driven system is in an air combat simulator (an example of which is in use in the UK at RAF Coningsby) as, within limitations due to mechanical complexity, it can meet all of the requirements indicated in section 3.2. It is not particularly suitable for air-to-ground applications, however, as the superposition of high resolution target areas on a low resolution background creates unrealistic visual cues and presentations. System characteristics are typically as follows:

(a) Spherical dome 8 to 12 metres in diameter, with the pilot's eye point at or close to the centre of the dome.

(b) A single or dual steerable projector system for each target.

(c) A single or dual steerable projector system (projecting a variable size light spot) to generate missile trajectories.

(d) Two or three fixed background projectors, located to achieve the desired field of view coverage, and projecting a sky and ground representation, with a resolution commensurate with projector angular coverage (and therefore usually quite low). In some cases this is replaced by a simple sky/earth' system, in which case no air to ground operation can be supported.

(e) Image generator requirements are for one channel per target and one channel for each background projector. (Minimum of 4 channels for a 2 target system.) If the simulator is limited to air-to-air combat only, however, an image generator of limited scene detail capacity can be used for the background and/or physical models and TV cameras can be used for the targets.

3.5.2.2 Comparison with Ideal System

The target-driven dome system compares with the ideal system (outlined above) as follows:

(a) Field of view is comparable.

(b) Image resolution, as far as the targets are concerned, is comparable.

(c) Scene content and level of detail are more a function of the image generator than the display system. However, whereas the target level of detail can be made comparable, the background will be degraded due to the large angular coverage per channel. Adequate cueing for aircraft motion is achievable.

(d) Brightness levels are typically low, (0.5 ft-Lamberts for background and up to about 2.5 ft-Lamberts for targets) as a result of the surface area over which the background image is spread and the need to match the brightness of the target with the background. Overall contrast is also generally low due to the characteristics of a dome as an integrating sphere, although laser target projection systems can achieve higher contrast for the targets. As the targets must be visible when projected on top of the background scene, they will always appear unnaturally bright. (This may in fact be desirable to ensure detection of the target is achieved at real world ranges despite contrast and brightness problems.) At the brightness levels found in such a system, the eye resolution is generally somewhat lower than optimum and indeed colour vision performance may be reduced as well.

3.5.2.3 Disadvantages

The target-driven dome system has the following disadvantages:

(a) Physical size of the simulator. Note, however, that smaller domes are sometimes used, and also partial domes, which can reduce this problem somewhat.

(b) Mechanical complexity of the projector systems (each target or missile projector requires at least three servos).

(c) Limited number of targets (3 or 4 maximum), due to projector complexity and physical layout restrictions.

(d) An aircraft HUD must be modified to ensure that the HUD focal length is the same as the distance to the dome surface.

(e) Low brightness and low contrast of scene. Daylight systems are at best very gloomy overcast light levels.

(f) Laser projection would be required with associated optical filters for each crew member to allow a two man cockpit to be used in a dome of this sort.

3.5.3 Line of Sight Slaved Systems

Three system types are considered here, namely a projected system with a fixed background, a projected system with a slaved background, and a helmet-mounted system. Examples of all these types of system currently exist.

Common to all three systems is a head position tracking device. The technologies used in head tracking systems are optical (usually with infra red cameras and illumination system), magnetic and acoustic. Each of these technologies has advantages and disadvantages in terms of relative accuracy, noise immunity, frequency response and transport delay. The projected systems are less affected by head tracker response and indeed transport delay in general than the helmet-mounted systems. This is because the relative spatial orientation of the image is fixed by the projection surface and thus, for a system projected on a dome, a transport delay in the sensing and image generation loop will result in the resulting image not being accurately centred on the pilot's head position. In a helmet-mounted system such an error results in the outside world appearing to move relative to the observer. Various forms of prediction

algorithms are employed to position the image correctly and eliminate this problem.

All of the above systems are suitable for use with an eye tracking system, though at present only the CAE-Link ESPRIT (Clifford and Jackson, 1992) and the CAE Electronics FOHMD (Morris and van Hemel, 1992) have operationally fielded eye trackers. For all these solutions, the sensing devices required imply that the pilot wear a special helmet in the simulator, rather than the standard issue helmet, and that this special helmet be close fitting to prevent excessive head to helmet motion which would compromise the accuracy of the head and, especially, the eye tracker.

3.5.4 Fixed Background Projected System

3.5.4.1 General characteristics

This system would be applicable to either an air-combat or ground attack simulator role. Currently this technology is represented by the CAE-Link ESPRIT system. Its essential characteristics are as follows:

(a) Spherical dome 7.3 metres in diameter, with the pilot's eye point 1 metre from the dome centre.

(b) One steerable projector projecting a circular field of approximately 20 degrees in diameter and with a resolution of approximately 1.5 arc minutes per pixel image on the dome surface.

(c) One fixed background projector projecting an image over 240 degrees horizontally by 120 degrees vertically. This field of view represents the total field of view of the system. The background resolution is approximately 20 arc minutes per pixel. The background system image generator channel provides for a "hole" in the background image at the location of the high resolution image, so that there are few superposition effects. (The system uses light valves as the light source which results in a non-black `black' image in the cut out which can affect the available contrast in the inset image.) The edges of the high resolution image are blended into the low resolution image so that discontinuities are less apparent.

(d) Image generator requirements are for one channel for the inset high resolution image and one channel for background, giving a total of 2 channels.

3.5.4.2 Comparison with Ideal System

The system compares with the ideal system as follows:

(a) Field of view is comparable, though somewhat restricted upward and rearward due to the projector system.

(b) Image resolution, as perceived by the pilot, is comparable.

(c) Scene content and level of detail are determined by the image generator and database and thus are affected as discussed in 3.4 above. The display system does not limit capabilities in this area, except where the available brightness and contrast may limit crew performance.

(d) Brightness levels are low (2 to 5 ft-Lamberts) due to the need to match projector outputs and the extremely wide field of view covered by the background projector. The high resolution projector image must be of the same brightness as the background image for a consistent presentation.

(e) The simulated aircraft cockpit is unaffected by the visual system requirements.

3.5.4.3 Disadvantages

The fixed background type of system has the following disadvantages:

(a) Physical size of the simulator, though the current application is mounted on a motion system.

(b) Mechanical complexity of the inset image projector. The servo requirements for these projectors are demanding in order to meet the rates required for head and eye movement tracking, however the system represents a good trade-off between complexity and performance.

(c) Projection of wide fields of view on the inside of a dome requires special optics and special mapping in the image generator to maintain uniform resolution.

(d) Due to the nature of the system, aircrew trainees must be fitted with a special helmet, which has to be aligned prior to use of the system.

(e) The eye monitor is a complex system, and some subjects may not be trackable, in which case the

system defaults to a head-slaved device.

(f) Only single seat applications can be supported without dividing the cockpit or using polarized images, in combination with polarizing filters, to enable each crew member to see separate images. Such polarizing systems have a lower brightness as a result of the filters.

(g) Total field of view (TFOV) limited to the background projector field of view, typically 240 degrees horizontally x 120 degrees vertically.

3.5.5 Slaved Background Projected System.

3.5.5.1 General characteristics

A current example of this type of system is provided by Evans and Sutherland and is known as VistaView. It is aimed at fulfilling the same role as the ESPRIT and FOHMD systems. At present it is not equipped with an eyetracker. Its essential characteristics are as follows:

(a) Spherical dome 5 to 9 metres in diameter, with the pilot's eye point close to the dome centre.

(b) A dual steerable projector system, projecting a combined image consisting of a 20 x 26 degrees, high resolution (1.5 arc minute per pixel), elliptical inset centred within a 60 x 120 degrees low resolution (9 arc minute) background. The inset is optically blended into the background to avoid noticeable discontinuities. The total image is moved in accordance with head position. The size of the high resolution inset can potentially be 30 by 40 degrees or slightly larger.

(c) Image generator requirements are as for the ESPRIT, consisting of two channels, one for the inset area and one for the background.

3.5.5.2 Comparison with Ideal System

The system compares with the ideal system as follows:

(a) Field of view comparable, but is restricted, due to the size and location of the projectors. Is generally adequate for some air to surface requirements. (Line of sight angular range is approximately ±105 degrees in azimuth and ±40 degrees in elevation.) Some advanced systems may achieve a full 360 degrees in azimuth and +90 by -45 degrees in elevation.

(b) Image resolution is comparable in the inset region, much worse in the background. This comment is valid for non eye-slaved systems as the observer is able to look directly at the background scene. Tornado experience revealed that without eye slaving, pilot head motion was excessive as the inset region was steered on to objects of interest in the scene. Even with eye tracking, the fact that the eye tracker envelope did not completely encompass the range of eye motion possible, ie, it was possible to shift gaze to an area not covered by the inset, led to exaggerated head motion when, for example, looking behind.

(c) Scene content and level of detail are determined by the image generator and database and thus are affected as discussed in 3.4 above. The display system does not limit capabilities in this area, except where the available brightness and contrast may limit crew performance.

(d) Brightness is higher than for the fixed background system, as the projected field of view is less. Note that this system also uses light valves. (The system, as currently conceived, uses dual projectors for the background to boost the brightness level.) However, the brightness is still comparatively low, at 4 to 5 ft-Lamberts, but is dependent on dome size and dome coating.

3.5.5.3 Disadvantages

The slaved background system has the following disadvantages:

(a) Physical size of the simulator. Note this is the same comment for all dome displays.

(b) Mechanical and optical complexity of the projector system. Servo requirements are demanding in order to achieve the rates required for accurate head and eye tracking.

(c) As image resolution is only good in the centre of the display system, head movement can become excessive relative to the real world. An optically modified aircraft HUD must be used in the simulator, as in all dome display applications, to ensure HUD focal length corresponds to the display distance.

(d) Display brightness and contrast is generally low. Contrast levels of 30:1 background and 50:1 inset may be achievable.

(e) Only suitable for single seat cockpit applications, or as noted in 3.5.4.3 f above.

3.5.6 Helmet Mounted System

3.5.6.1 General characteristics

The helmet mounted system is applicable to all modes of operation. Currently this type of display system is represented by the FOHMD used for the Tornado Low Level Test Bed programme (figures 3-3, 3-4). Its essential characteristics are as follows:

(a) Two helmet-mounted optical systems, providing separate visual images, focused at infinity, one for each eye. Each image consists of a background area of 66 degrees vertically x 82.5 degrees horizontally having a resolution of 5 arc minutes per pixel, combined with an inset of 24 x 18 degrees having a resolution of 1.5 arc minutes per pixel. The individual eye fields of view are overlapped by approximately 35 degrees, yielding a total background field of view of 66 x 127 degrees. The insets may either be fixed in the straight ahead position, appearing in the overlap area, or eye-tracked, with the inset position controlled within the background area as a function of eye position. The display units incorporate a proprietary optical system which permits normal viewing of the cockpit instruments.

(b) Two image sources mounted behind the pilot, each consisting of two video projectors, one each for the background and for the inset with an optical system that combines and focuses the images on the input to a coherent fibre optic cable. Imagery for each imaging eyepiece is coupled to the corresponding helmet-mounted optical system via this flexible fibre optic cable.

(c) Image generator requirements are for 3 channels, two background to form each eye's background field and one inset shared between each eye. The system can also use 4 image generator channels to render a full stereo image to the wearer.

3.5.6.2 Comparison with Ideal System

The system compares with the ideal system as follows:

(a) Field of view is comparable, own aircraft structure is also viewable in scene.

(b) Image resolution, as perceived by the pilot, is comparable, when in eye-slaved mode.

(c) Scene content and level of detail are determined by the image generator and database and thus are affected as discussed in 3.4 above. The display system does not limit capabilities in this area.

(d) Brightness is 30-50 ft-Lamberts depending on the light source used. Contrast exceeds 50 to 1, as measured on the Tornado system. This results in a convincing daylight scene with full colour characteristics of eye useable.

(e) The system is suitable for two seat tandem cockpits.

(f) The system is compact, fitting on a standard motion platform and has a robust eye tracking system which is relatively simple to maintain.

(g) System can be used with an unmodified aircraft HUD.

3.5.6.3 Disadvantages

The helmet mounted display system has the following disadvantages:

(a) The observer must wear a special helmet which is heavier than a standard helmet. Helmet alignment needs to be carefully maintained for optimum performance, and each pilot must have a custom-made helmet liner.

(b) The cockpit environment is modified by the addition of extra lighting to allow unimpeded viewing into the cockpit, although the ready viewing of maps and other non-illuminated objects can be difficult. Cockpit canopy is not used in order to allow for optical head tracking.

(c) Current fibre optic cable system somewhat impedes extremes of head motion, and fibre structure and breakage cause deterioration of viewed scene. These current system deficiencies were intended to be resolved as part of Phase Two of the Tornado programme.

(d) Use of unmodified NVGs or other helmet mounted display devices is not possible. Such devices must be simulated in the inset channel.

3.6 Conclusions on Display Options

The following conclusions are offered:

(a) With emerging technology it will be possible to provide a visual display system that is capable of adequate training for a fast jet aircraft by using the area of interest design approach.

(b) If a complete capability for air-to-air and air-to-ground visual training is required in one simulator, any of the line-of-sight slaved systems are capable of supporting the requirement. Solutions utilising domes as display surfaces require optical modifications to the aircraft HUD to modify its focal length.

(c) Only a helmet mounted system, an example of which is the Fibre Optic Helmet Mounted Display (FOHMD), provides a bright, high contrast, infinity-focused image and allows for correct visual display representation for two crew, tandem cockpit aircraft without expensive splitting of the cockpit.

(d) None of the line-of-sight slaved systems restrict scene content and detail level. These parameters of the total visual system therefore are completely determined by the image generator processing capacity and the database content.

(e) Use of unmodified NVG equipment is not possible with the FOHMD, though simulation, using the inset channel, is feasible. All eye-slaved solutions are sensitive to helmet fit and alignment issues which may impact user acceptance of such solutions.

(f) System latency has a significant impact on area-of-interest display solutions as it can affect the relative position of the inset compared to the centre of regard, particularly in cases where rapid head and eye motion is involved. The impact of system latency is relatively greater for the FOHMD.

It is worthwhile noting that the Tornado simulator evaluation, as discussed by Foldenauer (1992), van Hemel (1992), and Scheider (1992), produced an unprecedented body of data with which to determine the merits and problems of the FOHMD, and indeed all other aspects of the simulator upgrade.

3.7 Future Development

The core technologies from which the simulation industry draws key elements, such as micro-electronics, fibre optics and display systems, are advancing rapidly, driven by consumer demands, particularly in the area of entertainment systems. These advances are expected to result in improvements in simulation systems in terms of higher performance image generators and higher performance display systems.

3.7.1 Developments Within Five Years

Within the next five years micro-electronic systems which take advantage of sub-micron manufacturing technologies will be common, with resulting improvements in the performance of image generators in the areas of speed and pixel and polygon performance capacity, as well as cost. The principal stimulus for such improvements will be the demand for mission rehearsal in military simulators. Without this demand, image generator development is likely to be driven towards lower cost systems aimed at the commercial trainer market place, where performance is already sufficient for trainer certification.

(a) Areas not requiring specific support

The advent of higher density storage media will permit improvements in databases. This area will also benefit from general developments taking place throughout the computer graphics industry to support everything from CAD/CAM to entertainment. The commercial IG market is also driving this area towards the incorporation of satellite imagery, and other image sources, into visual databases.

Display system technology is being driven, by the requirements of the entertainment industry, towards the HDTV format which will have immediate benefits for the simulation industry. For example, the latest LCD projector technology was proposed for the planned follow-up of the Tornado project. CRT projector technology is expected to support 4 million pixel formats along with increased display brightness.

(b) Areas requiring support

With continued demand from the military, for example as a result of the Tornado and Harrier simulator programmes, image generators able to render up to 4 million pixels and up to 10000

polygons per channel, at 60 Hz, can be anticipated within the next 5 to 10 years. The planned follow-up of the Tornado programme called for 1.5 million pixels and 6000 polygons per channel.

Display system technology will require dedicated development activity if high resolution and high brightness raster-scan displays are to emerge with calligraphic capabilities to match that of the raster. LCD display technologies also require development to improve the dynamic response of the LCD crystals. The commercial market place is unlikely to provide all the incentives required for these developments.

Military requirements, exemplified by the Tornado and Harrier programmes, for reduced latency in the image generation loop are expected to result in greatly improved head and eye tracker performance within the next five years, indeed within the planned follow-up of the Tornado programme.

3.7.2 Expectations for the Longer Term

The micro-electronics industry is expected continually to improve the performance of systems and devices. Indeed, continuing trends indicate that a doubling of performance every 1 to 2 years is not an unreasonable expectation. Again, assuming there is a continuing demand for improved training system performance, these core technology advances can be anticipated to have direct impact on trainer visual display performance.

Longer term enhancements could include:

Micro laser or other micro projection systems for helmet mounted display solutions, eliminating the need for cables to carry the display information to the wearer, and with greatly reduced weight relative to current systems.

Image generator solutions capable (with area of interest solutions) to approach the scene densities encountered in the real world.

3.7.3 Fundamental Limitations

The preceding subsections have dealt with the anticipated improvements that can be expected as a result of the rapid advance of display systems technology. Some areas where fundamental physics prevents significant change are:

(a) Domes

It is unlikely that dome display solutions will ever be significantly brighter or have higher contrast, due to the fundamental nature of a spherical display surface as that of an integrating sphere. Thus light projected in a dome is spread about the interior surface via multiple reflections. Use of such a display solution for the presentation of wide field of view scenes required for air-to-ground training will always require that the scene is of relatively low brightness, in order to achieve acceptable contrast ratios.

(b) Display Resolution

There is a fundamental conflict between the desire for higher display resolution and higher brightness. This is because the smaller spot size, on a CRT faceplate, for example, required for the higher resolution, must be of a higher intensity to have the same relative visibility. A trade-off between resolution, contrast ratio and brightness will probably always be necessary except, perhaps, with laser display technologies.

(c) Contrast Ratio

There are no display systems currently available which can provide a true black image (unless they are switched off), while simultaneously providing a very bright light point, for example. This is due to the available contrast ratio of the projection system. While contrast ratio is expected to improve, it is not expected to reach the level typically found in a night scene, without radical change in the display technology employed.

3.8 Recommendations

Area of interest display solutions offer the best available technology for the present and the medium term to satisfy the need to provide low level flight training in a synthetic training device. Research into the contribution of detailed and peripheral vision to the overall perception of the scene as perceived by the observer is an area which would be of significant benefit. The information gathered would allow better specification of the image generator performance requirements for the background and inset channels of such display solutions.

4 MOTION CUEING ENVIRONMENT

4.1 Introduction

This section will consider primarily non-visual motion cueing. The requirement for *non-visual* motion cueing in flight simulation has been, and continues to be, the subject of much debate. In general terms the need for motion cueing depends upon many factors which include the task the pilot is required to fly, the handling qualities of the simulated vehicle, and whether the pilot is required to achieve the same level of performance, with the same workload, by employing a similar control strategy in the simulator to that employed in the real aircraft.

Before considering the low altitude, high speed role, a review of the principles involved in motion perception is important, since different cueing devices stimulate different human sensors, and the information the pilot is able to derive from these sensors also varies.

Human perception of self-motion results from a complex system of motion and force sensors. Broadly speaking, self-motion is deduced from visual motion perception and from what is sensed by the vestibular (inner ear) sensors, and the haptic system (force/pressure and kinaesthetic receptors in the body; see appendix A). Peripheral vision can provide very powerful motion cues (vection). Vestibular cues enhance the onset of vection. When flying at high speed and low level, rapid onset of vection may be required to recognize and anticipate hazardous situations in time. In addition onset cues should be simulated by a motion system when a wide angle visual system is in use, because such visual systems are a powerful tool to induce vection. However, without correctly harmonised onset cues this may cause cueing conflicts leading to simulator sickness (USAF, 1991). Appendix A deals with human motion perception in more detail.

Non-visual motion cues are very important to the pilot because they provide information the pilot cannot visually perceive. In addition, these cues do not require the pilot's attention and are difficult to suppress. In summary, therefore, visual and non-visual motion cues are complementary and one can not be considered as a substitution for the other.

4.2 Sources of aircraft motion

As an aircraft flies through the air, its airframe and consequently the pilot, is subjected to varying forces resulting in aircraft motion. For the purposes of discussing the pilot's cueing environment, aircraft motion may be divided into two categories, manoeuvre motion and disturbance motion (Gundry,1976).

(a) Manoeuvre motion

Manoeuvre (or commanded) motion arises from pilot control activities in the frequency range of about 0.1 Hz up to a maximum of about 3.0 Hz for fast jet pilots and helicopter pilots. This source of motion can be further divided into motion resulting from open loop control and closed loop control. Open loop control *predominantly* involves low frequency inputs, for example during a flight path change or a speed change. Closed loop control, however, involves the pilot making continuous high frequency, low amplitude inputs in immediate response to the aircraft motion. This type of control strategy can be observed in precision tracking tasks, formation flying or in the control of low stability aircraft. Generally, the tighter the pilot tries to control the response of the aircraft the higher the frequency of his inputs. When operating at these high frequencies the pilot is said to be employing a high gain, closed loop, control strategy.

(b) Disturbance motion

Disturbance motion often has a stochastic nature and can be subdivided into continuous disturbance motion (turbulence, engine vibrations, buffeting), and discrete disturbance motion (large gusts, windshear, stores release). Continuous disturbance motion acts like a stressor and can considerably increase pilot workload, thus giving rise to a more realistic feel to the simulation.

4.3 Motion Cueing Devices

A fundamental attribute of all attempts to provide motion cues in ground-based simulators is that it is impossible, for physical reasons, to replicate the full-scale experience. This is in marked contrast to other cueing systems where the true-life replication of sounds, control inceptor forces and displacements, and even the visual scene is attempted. Therefore, the aim of motion cueing devices is not to replicate the actual forces and accelerations (the stimulus) acting upon the pilot but rather to provide the pilot with a usable motion cue such that he reacts and behaves as if he was subjected to the real forces and accelerations.

A motion **cue** can be considered as a cluster of **stimuli**,

perceived by the pilot through a variety of sensors, which are closely correlated with some aspect of the dynamic response of the aircraft. These motion cues may be categorised as either onset, transient or sustained cues. This classification is a function of the cue timing and its duration. Onset cues occur immediately after initiating a manoeuvre or in immediate response to a disturbance and are of a short duration, whereas sustained cues are approximately constant and act over longer periods of time. Transient cues occur in the mid range between onset and sustained cues.

It is important to realise that for manoeuvre motion onset cues to be effective, they must be supplied to the pilot as soon as possible after the stimulus. If the simulator suffers from long latency or transport delay (higher than, say, 100 ms) or if the motion cueing hardware has a large phase delay (greater than, say, 30 degrees phase lag at 3 Hz) then the simulator may not provide a usable onset cue to the pilot. The actual tolerable latency and phase delay are primarily a function of the pilot's control strategy, the simulated aircraft dynamics and the flight task. The most demanding situation is when the pilot is employing a high gain closed loop control strategy.

Motion cueing devices can be roughly divided into onset cueing devices and sustained cueing devices. For onset cueing, the device must stimulate the pilot's fastest sensors and receptors - the vestibular system and the haptic system (see Appendix A). Sustained cues are generally based on force or pressure cueing systems that do not subject the pilot to a certain level of acceleration but rather provide the pilot with the illusion of being subjected to this acceleration through localised pressure changes. This illustrates the difference between a cue and a stimulus. The stimulus itself does not have to be an exact copy of reality as long as it provides a usable cue to the pilot. The fact that the g-suit pressure increases, for example, stimulates the pilot to think that the g-level is increasing, even though the actual g-environment is missing during ground-based simulation.

A trend can be observed, especially for fixed wing fast jet and helicopter simulators, towards in-cockpit cueing devices. A wide range of devices is still the subject of research. An overview of such devices is presented in Cardullo (1992). In the discussion here, the commonly available cueing devices are reviewed.

4.3.1 Motion platform

Motion platforms provide cues based upon whole-body motion which provides the advantage of simultaneously stimulating both the vestibular and haptic systems, although attenuated compared to real flight. They are capable of providing very good onset cueing and are especially suitable for the cueing of manoeuvre and discrete disturbance motion. Platform motion systems are also capable of providing, to a limited extent, sustained longitudinal and lateral accelerations. This is achieved by tilting the cockpit to re-align the gravity vector.

Due to the operational limits of motion platforms (achievable displacement, velocity and accelerations), they cannot produce the actual accelerations generated in a real aircraft. However pilots use changes in acceleration as a primary motion cue, therefore, high pass wash-out filters are incorporated in the motion system drive laws. These filters pass the initial aircraft acceleration (the motion cue) but will gradually decrease ("wash out") this acceleration immediately afterwards in order to avoid the motion platform hitting its mechanical stops. The motion drive laws also direct the platform back to its neutral position and introduce a roll or pitch tilt to generate sustained lateral or longitudinal accelerations. The selection of drive law characteristics requires careful consideration to match aircraft dynamics to the motion platform limits, since an incorrectly set up motion platform can lead to negative cueing and simulation sickness.

In order to cover the manoeuvre motion frequency range, the motion platform should have a bandwidth of at least 4 Hz. [*Bandwidth is defined here as the lowest frequency at which a sinusoidal motion input signal results in a motion system response having 45° phase lag or an amplitude attenuation of 3 dB.*] The low bandwidth of many older platform motion bases made them unsuitable for fast jet simulators because they simply could not follow the rapid attitude changes. However, since large synergistic motion platforms with a bandwidth up to 4 Hz have become available the application of these systems for fast jet aircraft simulators has become increasingly common.

For high-gain closed-loop tasks, the sway (sideways), roll and pitch degrees of freedom are of primary importance (Staples, 1978). Heave (vertical) cues can be very effective, too, provided that large travel is available. Otherwise, in-cockpit devices should be considered. The US Military Standard (MIL-STD-1558), requires a total vertical travel of at least 1.72 m (68"). Surge cues can be very valuable during take-off and landing and when the afterburner is activated. The yaw degree-of-freedom can provide strong cues especially

when dealing with a multi-engine aircraft, for example in the event of an engine failure.

4.3.2 G-seat and dynamic seat

G-seats were originally designed to generate sustained normal acceleration motion cues which cannot be generated with a motion platform. This is achieved by stimulating the haptic system using moveable panels and/or inflatable bellows. These panels and bellows exert pressure on the pilot's bottom, back and thighs whereby the illusion of whole-body motion is induced. In addition, a servo-driven lap belt may be used to provide stimuli resulting from acceleration in the aircraft plane of symmetry.

Multi-axis G-seats or dynamic seats primarily generate cues along the vertical, longitudinal and lateral axes, and have been shown to enhance lateral and vertical control performance (McKissick & Martin 1980). Early pneumatic designs had a low control bandwidth (typically less than 1 Hz) which made them unsuitable for simulating onset cueing. However modern dynamic seats have much higher bandwidth (typically 6 Hz) and have demonstrated good onset cueing, both in isolation and when used to complement and enhance platform systems (Keirl et al, 1995).

4.3.3 Vibration systems

In an attempt to create a workload environment as real as possible, continuous disturbance motion should be generated. Due to the frequency content of these vibrations, about 3 to 20 Hz (Cardullo, 1992), it is advisable not to have these cues generated with a motion platform but with an in-cockpit device like a seat-shaker. These systems are capable of reproducing vibrations due to engines, aircraft buffeting and turbulence approximating acceleration levels up to 2 g.

4.3.4 High-g cueing

None of the aforementioned devices is capable of simulating a true high-g environment. Only centrifuges can provide the g-levels as experienced in the actual aircraft, but disturbing side-effects (eg. "tumbling" sensations during acceleration and deceleration of the centrifuge) make them inappropriate for mission training.

Inflating the anti-g suit the pilot normally wears, as a protection against high-g forces, provides a strong cue even though these high-g forces are not actually present. The capability to drive the aircrew standard aircraft anti-g suits is, by and large, a normal component of the g-seat devices now on the market.

Although low altitude, high speed flight does not expose the pilot to extremely high g-levels (unlike air combat manoeuvring), the g-environment will affect the pilot workload. Even though the stimulus may not be as strong as in real flight, other devices like a helmet loader, arm loaders and partial positive pressure breathing systems, which have been used so far only in research simulators, give the pilot a usable cue. Helmet loaders, for example, have been shown to improve pitch control of the aircraft (Ashworth & McKissick, 1978).

The disadvantage with arm loading devices is that the pilot has to wear a special suit to accommodate the actuators. Partial positive pressure breathing systems provide extra (positive) pressure in the pilots breathing mask during high-g manoeuvres. These systems, however, must be used with care because of medical aspects; the pilot is actually **not** under high-g conditions. Especially, adverse use of normal "straining" techniques (which are employed when under high-g) can lead to potentially dangerous situations in a simulator.

Although not discussed in detail in this chapter, visually induced motion perception can also be used when simulating high-g manoeuvres. The visual system can, as a function of g-level, dim the total brightness of the image, shift the colour spectrum and/or create tunnel-vision effects. These are all effects the pilot, in most cases, encounters during (sustained or high-onset) high-g manoeuvres.

4.4 Pilot behaviour

4.4.1 Pilot behaviour in low altitude, high speed conditions

Low altitude, high speed manual flight places high demands upon the pilot's basic handling skills, and requires sustained high levels of attention and concentration. This high workload may be further increased by poor aircraft handling qualities, hostile threat sources and continuous disturbance motion. Furthermore, effects of topographical features, such as mountains, can give an extremely turbulent ride, which can make accurate control difficult. Another key factor in low altitude, high speed manual flight is the short time available to recognise and react to hazardous situations. Engine and system failures which might be recoverable at even medium altitudes will more often result in the loss of an aircraft when they occur at low

level.

Low altitude, high speed mission rehearsal is probably best characterized as a typical closed loop control task in which the pilot will employ high-gain behaviour. Due to this high-gain environment the frequency content of the pilot control activities may show a tendency towards the upper end (2.0 to 4.0 Hz) of the manoeuvre motion frequency range.

4.4.2 Peace-time versus war-time conditions

Mission rehearsal simulation should provide stresses and workloads that are encountered during execution of the actual mission that are as realistic as possible (Wiggers et al, 1989). There is, however, a major difference between peace-time and war-time behaviour. While in war-time both the primary task ("staying alive" in a hostile environment) and the secondary task (fulfilling the mission) are objectives of the pilot, peace-time control behaviour will show a lower gain due to a more subdued primary task (no real hostile environment and higher training altitude).

Although it is impossible to replicate a real war-time environment in simulation, potential threat sources can and should be accurately modelled in order to expose the subject to high-stress workloads. Motion and force cueing devices can play a psychophysical role in this process because, as part of the disturbance motion effects, they provide a capability to increase cockpit workload (Foldenauer, 1992).

4.4.3 Previous Research

The use and value of non-visual motion cues, and in particular platform motion, in flight simulation continues to be the subject of much debate within the simulation community. A recent meta-analysis carried out by the Naval Training Systems Center (Jacobs et al,1990) included an investigation into the impact of motion on the transfer of training for jet pilot training. A meta-analysis applies statistical techniques to previous research results to aggregate and transform individual research outcomes into a common effect and trend. This NTSC report reviewed 247 research and technical reports on the transfer of training for simulation based air-crew training, of which 26 (19 jet and 6 helicopters) had sufficient information to enable a meta-analysis to be undertaken. From these reports only 5 explicitly investigated the impact of platform motion on the training of jet pilots. This meta-analysis report concluded that

> "evidence indicating that motion cueing adds little, or nothing, to the jet simulator training environment cannot be considered definitive".

Furthermore the report questioned the validity of findings of this previous research due to;-

> "1) a lack of periodic calibration of the motion cuing systems",
>
> "2) the results were based on all tasks combined. The positive effects of motion for any one task may have been masked by the negative effects of motion for another task"

In addition none of the findings from the transfer of training experiments analyzed in the motion/non-motion case were carried out with modern motion platforms. All the findings relate to work carried out in the mid-to-late 1970's. Platform motion systems and the host simulations have improved since that time. In particular the importance of a low throughput delay and low latency configurations is now appreciated (White, 1995). The report highlights that motion effects vary from task to task depending on the primacy of motion cues for performing critical aspects of the task, and that the pattern of results indicates that motion cueing may aid certain training tasks. It has been shown in various studies, (eg paper 24 in AGARD, 1991) that simulating motion and force cues result in a pilot control behaviour that is more like the strategy employed in real flight, especially during high-gain closed-loop manoeuvring.

4.4.4 Summary

In summary, the vestibular system should be stimulated, preferably using a motion platform. Sway, heave, pitch and roll cues will have the greatest influence on simulation fidelity with respect to the specific low altitude, high speed mission rehearsal task. Special emphasis should be put on platform motion in a frequency range up to 3 Hz. As an alternative a dynamic seat may be used to stimulate the haptic system. These devices have been demonstrated to provide high fidelity motion cues for some mission task elements.

The requirements imposed by the physical location of mission rehearsal training devices can affect the way in which simulator components can be used. If a simulator must be as close to the theatre of war as possible to avoid the serious inconvenience of flying pilots to their

home base for training, the mission rehearsal simulator would need to be readily deployable. This requirement would obviously affect the use of a motion platform and probably eliminate it entirely, although the development of electrically driven motion platforms may influence any decisions. In-cockpit non-hydraulic motion cueing seats are probably the best solution for deployable simulators.

4.5 Current practice

The number of (platform) motion bases used in fast jet simulator applications is small. In most cases some combination of g-seat, anti-g suit or vibration seat is preferred for various reasons. Although simulators used in research environments are often equipped with a motion base system, a deep rooted tendency exists to eliminate this item entirely for military training applications.

Looking, however, to both the British Harrier GR5/7 full mission trainer and the German Tornado VTS simulator programme, inclusion of platform motion was part of the systems specification. In both cases, synergistic platform motion is combined with g-seat and anti-g suit to provide a broad range of motion cues.

These two simulators could potentially provide useful data on the value of motion cueing in such a context. To date, however, only data from the Tornado simulator has been available during the preparation of this report as trials have been carried out with a large number of aircrew. Evaluation results from both experimental and troop (aircrew) trial phases indicated a positive contribution of the synergistic six degree of freedom motion platform during task execution. The results were biased slightly in favour of platform motion by the Tornado Weapon Systems Officer (WSO) - the normal "back seater" - although no specific negative comments were made by the pilots.

From the final report (Foldenauer, 1992) on the evaluation of the Tornado simulator upgrade programme (phase 1), the following conclusion is presented:

> "Due to the particular importance of primary cues, a motion platform is considered essential, even if it is to be expected that this will result in an increase in crew workload. During instrument flight phases and during aerodynamically demanding manoeuvring it provides the only means of motion cueing.

Another conclusion from Foldenauer (1992) is:

> "Simulator flights cannot be 100% realistically represented, but they can present the crew with cues necessary to let them react according to real flight and as such can consolidate existing behaviour patterns or can even develop new ones."

During the preparation of this report, a visit was also made to the AH-64 Apache Combat Mission Simulator at Ft. Rucker, Alabama (USA). Although, as a helicopter simulator, it lacks the high-speed element in its basic scenario, experiences with the platform motion bases installed for both pilot and gunner were indicated as positive. Realism was increased compared to fixed-base simulations, especially with regard to the gunner's workload. The combination of platform and vibration seat induced motion perception was strongly felt as essential for this type of simulator.

4.6 Conclusions and recommendations for future research

In general terms the need for motion cueing depends upon many factors which include the task the pilot is required to fly, the handling qualities of the simulated vehicle, and whether the pilot is required to achieve the same level of performance, with the same workload, by employing a similar control strategy in the simulator to that employed in the real aircraft.

Non-visual motion cues such as platform motion and G-seats are very important to the pilot because they provide information the pilot cannot visually perceive. These cues do not require the pilot's attention and are difficult to suppress, therefore, visual and non-visual motion cues are complementary and one can not be considered as a substitution for the other. In addition, the application of properly harmonised non-visual motion cues can enhance the motion cues perceived by the pilot from the visual system.

A review of research literature into the influence of platform motion on the transfer of training for fast-jet pilot training revealed no modern research on this topic. A recent meta-analysis questioned the validity of earlier research. Cueing research has indicated that the impact of motion cues will vary from task to task. Therefore, there is a clear case for research to investigate in which tasks non-visual motion cues enhance the transfer of training, with particular emphasis on the low altitude regime. US and European views on the role and value of motion cueing in training simulators differ; further research should be undertaken on this.

The recent Tornado simulator programme investigated the use of platform cueing for low altitude, high speed mission training. A transfer of training experiment was not carried out, but aircrew subjective comments were obtained via structured questionnaires. In general, crews liked the motion system and felt that it made the simulation feel more realistic and that it contributed to the achievement of a similar working "environment" to that in the aircraft.

There is likely to be a requirement to site any mission rehearsal device physically as close to the theatre of operations as possible to avoid the serious inconvenience of flying pilots to their home base for training. Any mission rehearsal simulator may, therefore, have to be readily deployable. This requirement would impact on the specification of a motion platform and may eliminate it entirely. However, this increases the importance of other non-visual devices for motion cueing, such as dynamic seats. Research should be undertaken to identify the applicability and value of these types of device.

APPENDIX A

Basic principles of human perception of self motion

The information given in the following paragraphs is primarily taken from AGARD (1980) and Martin (1992).

A.1 Vestibular organs

Motion cues are sensed in the vestibular organs which are located in the inner ear. These organs comprise the semi-circular canals and the otoliths. Depending on the stimulus frequency, the semi-circular canals are more responsive to angular acceleration (below 0.1 Hz) or angular velocity (between 0.1 and 1.0 Hz). Otoliths are responsive to specific force stimuli (i.e. the kinematic acceleration minus the acceleration due to gravity). With respect to stimulation frequency these organs are sensitive to normal head motion (between 0.03 and 0.24 Hz).

A.2 Haptic system

In the haptic (or tactile) system, force and pressure applied to the skin is sensed as well as the relative movements and position of various parts of the body (e.g. head and limbs). These stimuli, respectively sensed by tactile receptors and kinaesthetic receptors, are translated in the central nervous system resulting in a motion sensation.

Kinaesthetic receptors sense the muscle forces required to hold limbs, body and head orientation. These receptors therefore provide information on the forces applied to, and hence the acceleration of, the body. They are found in the joint capsules and the ligaments about the capsules.

Receptors that are active in the haptic system show a large variety. Some of them adapt very quickly, meaning that the sensitivity to a stimulus changes under continued exposure to that stimulus. Those which adapt quickly show time constants between 1 and 10 ms. Others adapt in between 1 and 30 s, or only partially adapt. The latter type of receptor is found in the deeper layers of the skin and is important in signalling continuous skin deformation.

A.3 Visual perception

The eyes detect motion essentially as a change in position or, to a lesser extent, velocity in peripheral vision. They detect acceleration and velocity by assessing changes over a period of time, and are responsive to low frequency stimuli (below 0.1 Hz). Because the eyes are capable of sensing self-motion without showing adaptation they provide a steady state motion reference.

Peripheral vision can provide very powerful motion cues (vection). The onset of vection can be hastened by stimulation of the vestibular system to typically tens of milli-seconds. However, in the absence of vestibular stimuli the onset of vection can require 5 to 10 seconds. Conflicting vestibular cues will delay and, in the worst case, result in loss of vection. It is important to note that the eyes <u>are</u> capable of sensing self-motion.

The sensitivity of visual and vestibular sensors to motion stimuli vary as a function of input frequency. At higher frequencies the vestibular system dominates vision, whereas at low frequencies vision dominates. These sensors can therefore be regarded as acting in a complementary way.

CHAPTER 5

DATABASE SOURCES AND LIBRARIES

CONTENTS

1 SUMMARY

This chapter addresses the use of various databases and data libraries within a mission simulator to satisfy operational needs. It also addresses how to model the aircraft to achieve the required fidelity. It then discusses issues concerning the acquisition of data and the system integration problems associated with database correlation and data fusion. It considers the performance to be expected from image generators and the consequential effect on database requirements and visual presentation.

2 INTRODUCTION

The purpose of this chapter is to review the extent to which data sources and libraries support or limit the simulation of low altitude high speed training and mission rehearsal. A mission simulator should aim to:

(i) Provide adequate simulated sensor scene content

(ii) Optimise the database in relation to image generator and display system performance (particularly for visuals)

(iii) Accurately model (own-ship) aircraft performance

(iv) Accurately model a database for mission rehearsal to portray the battle environment and scenario

(v) Correlate databases across simulators and sensors

(vi) Reduce database preparation time

(vii) Re-use databases

This chapter will discuss the extent to which these objectives can be met, either now or in the foreseeable future.

3 SCENE GENERATION

3.1 Outside world scene

Simulation of sensors requires libraries and databases of modelled information for their realistic operation. Potentially, depending on the equipment fitted to the aircraft and on the mission profile, the following sensors that provide a "scene" of the outside world need to be simulated:

3.1.1 The human eye

Simulation systems are needed to provide a view of "out-of-the-window" scenes as seen directly by the pilot, by day and by night, and under varying visibility conditions.

3.1.2 Electro-optic sensors

The outside world scene is also observed indirectly by the pilot using the on-board electro-optical systems. These can include:

(i) Night Vision (NVG) systems

(ii) Forward Looking Infra-Red (FLIR)

(iii) Infra-red Imaging System (IIS), e.g. for reconnaissance

(iv) Low Light Television (LLTV)

(vi) Radar

Ground Mapping Radar (GMR), Synthetic Aperture Radar (SAR), Sea Search modes; Air Intercept (AI) modes including Track Whilst Scan (TWS), Lock, Air Combat, Target Illumination, Target Ident, Radar Altimeter, Terrain Avoidance/Terrain Following etc.

3.2 Visual image generation

This section will be mainly concerned with the visual

image generator (IG). The current and expected future capabilities of IGs to meet the needs of low-level mission rehearsal for sensor and out-of-the-window visual simulators are addressed. The purpose of the image generator is to select and process a set of pre-formatted data to generate in real-time (at least 30 times per second, 30 Hz, and preferably, for the demanding high-speed low altitude role, 50 Hz) a picture of the outside world. The complementary hardware component, to display the visual scene, is discussed in Chapter 4.

3.2.1 Real-time database capacity

Selection of data that is appropriate to the task in hand is done by the real-time database management system. This selection is necessary to ensure that the IG is not overloaded; that the displayed scene contains information optimised for the current task; and that data for the whole gaming area are available as the aircraft flies over it. This involves, for example, the selection of models at the right level of detail for the viewing distance and task needs, and ensuring that key objects, such as targets, are retained while less important objects might be removed.

3.2.2 The gaming area

The size of the gaming area will be determined by the mission to be rehearsed. There is no restriction, if data are available, on this size beyond the time and cost to produce the database. Typically, the total database is held on a disk with the potential "in range" data being down-loaded in real-time to high-speed memory to form the real-time database. Advances in memory technology ensure that there is no problem in providing the storage capacities needed to satisfy the IG capabilities. The number of object models to be available should match the polygon processing ability of the IG.

3.2.3 Scene detail and resolution.

The real-time database must hold data with the level of detail and with the modelling resolution that is intended to be displayed. Three classes of data are used: the terrain model, cultural objects (natural and manmade) and animated objects such as moving targets. All of these classes of data may be enhanced in appearance by the use of texture, including photo-texture, and may be presented at different levels of detail.

3.2.3.1 Terrain model

The terrain model, representing the shape of the landscape, is typically processed as a polygon model. This model is constructed as a best fit to the available data **and** to the polygon processing power of the IG. There are thus two constraints on modelling accuracy: the quality and resolution of the source data, and the filtering of this data to fit the number of available polygons for display.

The primary source of terrain data has been DLMS data, such as Digital Terrain Elevation Data (DTED). [*Note - DLMS refers to Digital Land Mass System whereas DRLMS refers to Digital Radar Land Mass Simulator. DLMS data is used to create instances of radar simulators.*] DTED is generally produced at Level-1 resolution (approximately 100 metre height post spacing), with certain areas at Level-2 (30 metre). At best, this means elevation data are available at sample points that are 30 metres apart, with no information available on what the terrain is doing between such points; this might be critical when flying at fifty feet. More typically, only Level-1 data will be available, at one hundred metre grid points.

Given the availability of level-2 DTED, to render all such data into a set of polygons would require an IG to process around 1 million polygons per channel for a 25-mile range over undulating terrain. This is two orders of magnitude greater than current systems can provide and is not likely to be attained in the foreseeable future. Thus undulating and mountainous terrain will necessarily be portrayed in simplified form. Flat areas can, of course, be represented with good fidelity with fewer polygons. More sophisticated polygonisation techniques can optimise the capabilities of a system by concentrating the polygon density over the more undulating areas and making use of irregular polygons to gain better fits to the terrain data. The particular optimising algorithms tend to be proprietary to the supplier, such that different sensor simulators may not use a common polygonisation process, potentially giving rise to correlation problems.

3.2.3.2 Cultural objects

Cultural objects that feature in and on the terrain are defined in DLMS Digital Feature Analysis Data (DFAD). Examples include urban areas, fields, woods, lakes, rivers, roads, railways, and single objects such as houses, factories or bridges. Additional synthesised objects are often added to enhance specific areas or to provide particular objects required for training purposes. The number of polygons devoted to such objects is a trade-off between the fidelity of the terrain, the number of objects and the object fidelity required for training.

The studies on the German Air Force Tornado simulator showed that a large number of three-dimensional objects were needed to provide height cues for low-level flight.

3.2.3.3 Animated objects

A certain number of objects need to be given some sort of movement. This can be within themselves (eg radar scanners), or objects with freedom to move with one to six degrees of freedom, either in the air (eg aircraft targets and missiles) or across the terrain (a tank formation). Again, polygons are needed from the total polygon budget to provide the degree of modelling necessary to achieve the training task. In some cases this task will require only detection of a target but it is often also necessary to recognise a particular type of target. Each independently moving object is associated with its own dynamic co-ordinate system for computing the object's orientation with respect to the terrain model's co-ordinate system and hence for computing the correct perspective to the viewing eye point. Each such moving object must be commanded to move in some way. In the case of a ship, it may be sufficient simply for it to proceed at a fixed heading and speed across a two-dimensional sea; an aircraft target may be making 'intelligent' tactical movements to combat the actions of the own-ship aircraft; a tank may be moving across undulating terrain. The consequence of the computing load implied by moving targets is that today's systems are typically limited to around 32 targets simultaneously in view and activated. Over the next five years it is not anticipated that this number will exceed one hundred in practical applications, even though the basic IG may support several thousand independent dynamic co-ordinate systems. This is the result of the computational power required within the image generator and the number of polygons that can be allocated to the visual appearance of the targets.

3.2.3.4 Detail enhancement by photo-texture

Photo-texture images can give the appearance of improved modelling fidelity for visual systems and allow for a reduction in the number of polygons required. However, there are data storage and band-width limitations as to how much photo-texture data can be accessed and processed in real-time. To ease this problem, and the logistics of obtaining specific photographic data, generic photo-texture patterns can be used to a large extent. Photo-texture however, of itself, does not provide true 3-D detail and polygons need to be used to model visually significant 3-D objects. The need to use actual polygons is also set by the requirement to provide height data for such sensors as terrain-following radar (TFR), to provide visual occulting, and to calculate obscuration and collision conditions. To date, the continuous creation of polygons to fit the DTED points to a specified polygon density (to suit the IG) has generally been too computationally-intensive to do in real-time. The growth in processing power now enables image generation systems to achieve this in real-time, and so allow level of detail (LOD) terrain modelling akin to that currently done with cultural objects.

Use is already being made of terrain data derived from stereo-pair satellite images. It is likely that this will become an increasingly important source with the advantages of wider availability and, in the next five to ten years, of greater resolution. This should mean that in the next five to ten years such data sources, combined with improved IG capabilities, should enable terrain to be portrayed to sufficient resolution to satisfy low-level flying requirements over most terrain types. Research will be necessary to establish criteria for scene detail and to validate that the transfer of training is indeed sufficient.

The level of detail required to simulate realistically such high resolution sensors as synthetic aperture radar (SAR) is beyond the resolution of level-2 DTED, the availability of which is also limited. Again the answer is the use of stereo-pair satellite images. Future commercial systems (eg SPOT-5) are forecast to have image resolutions down to five metres. Military reconnaissance satellites with a resolution of one metre or better at the centre of an image have been proposed (eg the French Helios satellite and the UAE Murakaba satellite).

3.2.3.5 Scene management for optimising detail and resolution

Level of detail management for objects has long been a feature of IGs to prevent scene overload. Database management is carried out by the real-time database system. This system needs to take account of how many polygons are being displayed and take measures to reduce the number if the capacity of the IG is being exceeded. This is typically done by removing objects completely or by replacing an object with one at a lower level of detail. A degree of sophistication is needed to avoid such removals being observable, and hence distracting, as well as to ensure that objects important to the mission are not removed. Such scene management is within today's capabilities but may be further enhanced in the future by the application of

intelligent knowledge-based systems and fuzzy logic.

Level of detail management is also applied to selecting appropriate texture and photo-texture patterns. It can be expected that real-time databases will include photo-texture patterns to the highest level of detail required for the mission. However, for normal sizes of gaming areas, the total amount of high resolution data for the mission could not be stored for on-line use in the IG texture memories. The real-time database management system will allow texture patterns required for immediate use to be continuously down-loaded. Present IGs have now introduced photo-texture and tend to use limited photo-texture sources. For example, satellite photographs may be used for most of the area. This is adequate until the viewing distance becomes such that the resolution limit of the photographed images is apparent. Where there is an operational need to view the terrain or object at closer distances it is possible, in principle, to transition to a higher resolution source (eg an aerial photograph). However to generate such data and to deal with image processing issues such as ensuring consistency in colour balance, or time of day/year differences is a matter for ongoing research work. It may be some years before a rich source of such processed data is available from such sources as Project 2851 and its developments (see section 7.2). With low level flight, the texture patterns are often viewed at low grazing angles. This, in association with present texture anti-aliasing measures, means that texture alone does not provide totally adequate terrain cues at low level.

3.2.4 Real-time capability

Extracting relevant data from the on-line database and then processing such data to supply the visual display system with the video signals for the observable scene is done by the IG. The IG is the main determinant of the quality and appearance of the scene detail simulated, eg the number of objects, texture detail and modelling realism. The resolution with which the observer sees the generated scene is determined by the display system. IG capability is influenced by the following key factors:

(a) Scene content

The following factors contribute to the real or perceived information scene content of an image:

(i) Polygon capacity

Until recently the perceived scene complexity and degree to which the scene appeared cartoon-like depended on the capacity of the IG to produce polygons. Polygons are the primitives used to model the terrain surface and 3-D objects, including targets. The addition of the capability to overlay texture on polygons and, more particularly, the recent developments in using photo-texture have enabled very realistic images to be produced, so that demands on the polygon count to achieve realism are reduced. However, the illusion of "bumps and dips" provided by a photo-texture pattern overlaid on a flat polygon must be turned into polygon-modelled "bumps and dips" (sometimes called "micro terrain") when the aircraft is flying over them at low level. This will be a function of the scene management and online "polygonisation" of terrain data. For the low altitude high speed role, such capabilities should concentrate the polygons into that crucial sector of about two miles ahead and within ± 60 degrees horizontally. This online generation of higher levels of terrain detail should be available within five years.

Current mission and training simulators in use, such as the German Tornado and the UK Harrier GR5/7 devices, whilst specifying the best available systems at the time of procurement, do not have visual systems that represent the current state-of-the-art performance: they have problems in providing sufficient height and speed cues to fly visually at low level. Simulators to be procured in the next five years should have a polygon count, allied to powerful photo-texture, to support low-level high speed flying. It should be noted that the procurement time for the development, build, integrate and test cycle for a complex simulator has been greater than the time between successive generations of IGs!

Today's systems have between five hundred and four thousand polygons per channel, with all polygons fully anti-aliased, textured, and displayed. This capacity can be expected to rise to ten thousand polygons per channel in the near future, and even higher in five to ten years. However it might be that the drive to go to ten thousand polygons will be reduced because of the availability of powerful photo-texture. This may direct development into other areas of system improvement. Limitations on the bandwidth of input/output busses between subsystems may become a limiting factor for the number of displayed polygons.

(ii) Light points

There are two basic techniques for displaying light points: raster light points and calligraphic light points. The latter technique is employed in most visual systems used by commercial airlines where good light point simulation is required for training to simulate realistic runway lighting patterns. For military mission simulators, the requirements for light points are less demanding; here the use of raster light points is more cost effective and does not put a further constraint on the type of display system to be used. However, such light points cannot achieve the smaller spot size and high contrast of calligraphic light points. There is no inherent reason why a top-end IG could not have a calligraphic light point mode. However, the benefits would have to be cost-justified and the restrictions on display system types would have to be acceptable (i.e. the imaging source must be able to operate in a calligraphic mode).

Generating light points is at the expense, for a given frame time, of reducing the number of displayed polygons. For raster light points, most current systems trade one polygon for between one and three light points. If a large number of light points were a requirement it should be possible to incorporate special hardware into future designs to trade-off, say, one polygon for one hundred light points.

(iii) Rendering capacity

The quoted number of polygons is not the whole story: the capacity to render polygons to form displayed pixels is another important, but not often quoted, parameter. Rendering is the process of turning polygons into display objects, removing hidden surfaces and adding texture and visibility effects. Another factor is how efficiently the IG deals with hidden surfaces, as this can affect the effective rendering capacity. The rendering capacity might be specified as the number of times the whole screen of pixels can be over-written in a frame time. Given that a system deals with hidden parts efficiently, the main reason for having an overwrite capacity of at least three is to support heavy use of transparency. Transparency enables simulation of windows and use of cell texture for simulation of cloud effects, smoke, trees etc. Future state-of-the-art visual systems should meet these requirements, but there is a trade-off between overwrite capacity, pixel resolution and update rate when specifying a visual system.

(iv) Shading models

Current systems can support smooth shading, i.e. simulating curved surfaces from flat polygons when illuminated by a directional light source, such as the sun. Such models only allow for diffuse reflections. In the real world there are many examples of specular reflection, eg glinting targets. It may be that this capability will be added in the next five to ten years.

(v) Texturing capacity

Photo-texture, using full RGB colour on a large scale, is a recent feature in visual systems. Such a system is not yet deployed in use for mission rehearsal or training. It is believed that this feature now enables the visual system to provide the height and speed cues necessary to fly visually at low altitude, although further research is required to confirm this. Today's systems are still limited by memory and/or the ability to refresh that memory in real-time as a large database is traversed. The next five years should see the capability increased to support the use of terrain-specific photo-texture to meet operational needs.

(vi) Weather effects

Present day visual systems fall short of simulating the most demanding weather conditions in two ways. First, current visual technology does not provide for accurate simulation of three-dimensional variations in density of cloud and, in particular, fog structures. Secondly, atmospheric mathematical models that exist today are inadequate for many conditions experienced in operations.

To date, atmospheric models, when used, have been applied in the host simulator to provide the visual system with just a single visual range parameter in all directions of view. When true three-dimensional modelling of visual atmospheric structures becomes possible, then area-specific environment models must reside in the visual system.

Technology will be required to solve two problems: the design of a large real-time environmental database, and the provision of a high bandwidth interface to hardware pixel operations in the heart of the image generator. The environmental database

is mainly a software system, of considerable complexity, that may take a number of years to develop once satisfactory models are produced. Interfacing the image generator to the pixel operations is technically feasible today, but the production costs, with today's technology, are too high for manufacturers to provide. However, it is likely that continuing developments in custom VLSI/ASIC technology (Very Large Scale Integration / Application Specific Integrated Circuit) will increase the capacity for pixel operations for texturing and depth-related operations. Thus, the required environmental model interface would be economically viable within the next ten years.

(vii) Modelling constraints

Modelling constraints, imposed by the need to deal with hidden surface removal to avoid occulting problems, will be removed in future systems by use of pixel level range buffering ("z-buffering"). Z-buffering is commonly found in work-stations and is now appearing in higher-end real-time systems. It is expected that this will become standard over the next five to ten years. Pure Z-buffering, however, does not solve all the problems, especially in wide field of view systems, where slant range between objects and the eye point is the critical parameter.

(b) Image quality

(i) Anti-aliasing measures

As processing power increases, the use of more sub-pixels within each sampling point and the use of more sophisticated algorithms will be practical. This will lead to further reductions in spatial aliasing. However, the improvements that might be seen in a static image should also be judged when moving through the scene. In dynamic situations, the subjective benefits of further refining the spatial anti-aliasing may not be apparent and therefore not cost-effective to provide. For temporal aliasing, improvements may be expected by, first, the use of non-interlaced displays and, secondly, perhaps going for 80 Hz update rate within five to ten years.

(ii) Texturing Methods

A texture or photo-texture map is placed on a surface but may be viewed from a range of angles. The simple filtering methods applied to avoid texture aliasing can result in reduced resolution when viewing from other than the optimum directions. This is an area where some improvement can be expected within five to ten years.

(iii) Image "popping"

The use of Z-buffering in future generations of IGs will avoid the possibility of occulting errors that can sometimes be observed in today's systems because of modelling errors or system constraint violation. The "popping" in and out of objects by the scene management process should improve as more sophisticated techniques are employed for object selection and their fading in and out of the scene.

(c) Image update rate

To match the rapidly changing scene content in low-level high speed flight, the scene is re-computed at the display refresh rate which, for current systems, is 50 or 60 Hz. It would be desirable to increase the display refresh rate to 80 Hz to reduce the flicker that becomes more apparent with brighter displays. A further consequence of higher update rates in the IG would be to reduce latency. However there will always be a cost trade-off against the number of displayed pixels and the update rate, as well as a performance trade-off against the number of polygons and dynamic targets for a given processing power. To date this loss in performance has not seemed worth the gain from increasing the update rate; also, until recently, display technology limited such possibilities. Given the increasing capabilities of IGs and display devices, the trade-off balances could change.

(d) Latency

Latency is the transport delay from the host simulator to the image display. Achieving low latency is particularly important to slaved area of interest (AOI) displays. Latency time is largely determined by the number of frames required to compute the data to be displayed, typically three or four. Increasing the frame update rate to 80 Hz should be possible in five to ten years and this would reduce visual latency by 30%. An IG architecture that was more integrated with an AOI system could also reduce system latencies and the

first such high end systems will be available in a year or two.

(e) Resolution

(i) Pixel resolution

The final stage of the IG contains display data stored in a frame store structured as a matrix of picture elements (pixels), each pixel containing a discrete intensity and colour level. Current systems typically offer up to one thousand by one thousand pixels (ie 1 million) per channel at a 60 Hz update rate, with top of the range systems going up to 1.5 million pixels. The pixel is the smallest element that can be displayed. The display system (see chapter 4 for a more detailed discussion) "spreads" out these pixels across the field of view (FOV). Thus there is a relationship between the perceived display resolution (arc-minutes) and the number of pixels. This is a function of the displayed FOV for a channel. Thus one thousand pixels displayed across a twenty degrees horizontal FOV would give a resolution of 20/100 degrees (or 1.2 arc-minutes per pixel). In practice the display system will degrade this resolution to the observer because of its *intrinsic* display characteristics (Modulation Transfer Function). Obviously there is a cost trade-off between the number of channels and display systems and the resolution to cover a given FOV. There may also be practical difficulties in matrixing the display channels within an AOI display, so that display systems ultimately limit the achievable display resolution. As imaging sources for display systems improve in resolution, as can be expected over the next five to ten years, the IG technology should be capable of supporting increased resolution by computing more pixels. As well as displaying pixels along a line, there must be a sufficient number of raster lines to maintain, ideally, an equal resolution vertically and horizontally. One thousand pixels along a line enables 500 line pairs to be potentially displayed. One optical line pair equates to 2 TV lines, so a typical 1000 line system supports the display of static images of comparable horizontal and vertical resolution.

ii) Interlacing

Interlacing is commonly used to achieve the full system resolution on systems with a high update rate. However this is not ideal because temporal aliasing effects can occur (AGARD, 1981). Thus dynamic resolution is less than is achieved with static images. With increasing performance in both IGs and display devices, non-interlaced systems are likely to appear within the next five years.

3.3 E-O sensor image generation

3.3.1 Night vision goggles (NVG)

For NVG simulation, the direct daylight viewing visual system is normally used and viewed by the crew wearing their own NVGs. To provide an optimum image to the crew, the intensity levels need to be appropriately set. The limited dynamic range of intensity means that the visual IG cannot be used to provide images, such as flares, that might saturate the NVGs in the real world. The dynamic range can be improved by the use of calligraphic light points. It is not envisaged that future IG developments will address this issue and developments will mainly occur with the display technology. However the new generation of NVGs is less susceptible to such saturation. In using the IG for night scenes, the ability to portray large numbers of light points can be more important than for daylight scenes for fixed wing operations.

3.3.2 Forward looking infra-red (FLIR)

A typical FLIR IG is based on a single channel of a visual system IG. The output from this is fed to a post-processor that drives the FLIR display and simulates the characteristics of the IR sensor and the FLIR signal processing.

It is believed that visual IG technology will ensure that the needs of the FLIR IG will be met. The main issues are related to the database, particularly the extent that the thermal radiation of all objects and terrain should dynamically interact with each other over time. The complexity of such modelling is believed to be beyond the state-of-the-art capability for real-time simulation, even over the next five to ten years. Thus the issue of whether the dynamics of such behaviour should be done in the FLIR IG is not addressed. This is probably not too significant for the overall requirements for mission rehearsal, for which the modelling of the atmospheric effects on the sensor images of the objects and terrain with fixed, defined, thermal signatures is within today's capability and should suffice.

3.3.3 Low light television (LLTV)

A visual system IG can be used to provide the video signals to drive an LLTV display and the out of the

window and the LLTV views can use the same database. The IG would be adapted to give an acceptable monochromatic representation. The main issue with LLTV systems arises if the system gives a magnified image. In such a case the database optimised for the normal out of the window view will, when magnified, appear sparse in terms of object density. The visual scene photo-texture detail will appear, when magnified, as low resolution at close distance. To provide the same apparent scene density to the observer and to provide higher level of detail in the models for the whole gaming area is impractical, both in terms of storage requirements and database preparation. It would, however, be possible to provide high density scenes for limited areas that are mission critical. It is also possible to model key objects, such as targets, to higher levels-of-detail so that they appear realistic in magnifying sights.

3.3.4 Radar

Simulation of the radar requires IGs to process relevant data from the database similarly to the visual systems and provide the real-time processing to display radar images on the displays in the various modes. Previous full DRLMS radar simulators were very hardware intensive. Today, with the increase in computational power available, radar simulation is largely achieved in software together with VLSI/ASIC circuitry housed in a single cabinet. Continued increases in the computing power of RISC processors should ensure that radar simulator IGs will continue to match the operational need over the next five to ten years. The data processing update rates are much lower than required for a visual system IG so that the radar simulation IGs are usually capable of displaying more scene objects and detail than the visual system. The main issues are concerned with producing databases with the required content and adequately correlated with the other sensors and visual scene (see section 6 of this chapter).

4 OWN-SHIP DATABASE & LIBRARY REQUIREMENTS

Own-ship models can be categorised as generic core models or aircraft-specific models. Executive functions like task-scheduling, input/output-handling, etc. fall outside the scope of own-ship modelling.

Truly generic core models are few and consist mainly of equations of motion, including supporting functions like axis-system conversions, integration, etc (see McFarland, 1975; Tomlinson, 1979). Core models are generally not the limiting factors in aircraft simulation and no separate development is thought to be required for the low-altitude high-speed task in mission rehearsal simulation. However, too simplified numerical algorithms can lead to unwanted simulator characteristics - for instance when using Euler angles to define own-ship orientation instead of using quaternions.

For any reasonable high level of physical fidelity, each aircraft type will require a certain amount of aircraft-specific modelling. Individual simulation models are commonly used for own-ship aerodynamics, systems, engines and avionics to ensure the required level of fidelity is achieved.

4.1 Aerodynamic, systems and engine models

4.1.1 Fidelity

Fidelity is an important aspect of simulation. Simulator fidelity can be broken down into different categories, from equipment fidelity (mainly cockpit handling) to environment fidelity ("correctness" of the simulated world as perceived by the pilot); another approach could be to distinguish between objective and subjective fidelity. Such a distinction is often used when civil training simulators are accepted to comply with the FAA or CAA regulations.

The subject of this Report is low-altitude high speed mission training and rehearsal. The required fidelity must be adequate for the range of tasks that comprise this mission. Several tasks have been identified in chapter 2 on "Training Objectives and Mission Requirements". The following tasks particularly require good fidelity for the own-ship models in mission rehearsal simulation:

- Air-to-air refuelling: joining up, hold position, make contact, disconnect, depart
- Ingress/Egress: low-altitude high-speed flying, low-level navigation, air combat manoeuvring
- Attack: threat/evasion/handling, terrain masking, target acquisition
- aircraft battle damage.

4.1.2 Aerodynamic, systems & engine data availability

The data required to support the simulation can be categorised as falling into three types:

(i) Simulation Modelling Data (design data) to be used for the real-time simulation.

(ii) Verification Data to verify that the model has been correctly implemented (snapshot values for specified conditions, etc.).

(iii) Validation Data to be used to check that the system is performing correctly (e.g. flight test time histories, rate-of-climb, engine start-up history).

Data availability is often sparse over portions of the total simulation envelope and acquiring the data may often be a political and cumbersome process with country-dependant export license restrictions. In the frequent absence of models from the vehicle or system manufacturer, data have to be predicted, by interpolation or extrapolation, from snapshot data values. Care is necessary to avoid the consequent possibility of negative training if such prediction leads to an incorrect model.

When available, manufacturers' engineering models are often not suitable for real-time simulation (eg large execution times, long function search and interpolation routines, non-deterministic iterative techniques). However, they can be useful to provide validation of the simulator design.

There is a need with military simulators for flight tests and data gathering exercises dedicated to simulation requirements, as is common practice for commercial transport aircraft simulators. A typical approach would be to carry out static flight test measurements, backed by wind tunnel data, in a grid over the entire envelope. Careful analysis may reveal strong non-linear behaviour, which demands a finer grid. An entirely different approach is called dynamic flight testing (Mulder, 1986). This technique uses specific, dynamic manoeuvres to obtain data from which a continuous model can be derived. A limited number of measurements in the envelope are sufficient. This results in reduced cost for simulation model flight testing.

Mathematical models specific to low-altitude high-speed flight are not seen as necessary; simulation of the low altitude high speed role can be carried out by the standard available own-ship aerodynamic and atmosphere models.

4.1.3 Modelling effects of wind gust and turbulence

Current models of fast jet aircraft are typically based on single mass-point, rigid aircraft and a single environment flow vector. Technically it is possible to provide a more rigorous model using multiple mass-points, aircraft flexibility and multiple flow vectors (matrix wind models); large commercial jets use these (see Kaufman and Kindel, 1990; Mohlenkaump and Fegel, 1989; Campbell, 1984; Hahn et al, 1988; Flassak, 1990) because the aircraft size automatically implies that flexible modes are part of the normal flight envelope. However, for this low altitude high speed mission rehearsal application, it is judged that current mathematical models are sufficient, given that the environmental model supports terrain induced up-drafts and wind shear.

4.1.4 Need to model beyond the (normal) envelope limits

It is a requirement to provide full simulation up to and exceeding controllable flight boundaries. The need for simulation outside the normal envelope is driven by the regular occurrence of departure from the normal flight envelope during air combat manoeuvring. Extrapolating data is not suitable and flight testing outside the normal envelope is difficult. Such flight data can therefore be based only on wind tunnel measurements. Unless accurate data are available, negative and/or dangerous training will result.

Full simulation of aircraft performance for all configurations, including asymmetric conditions to simulate stores hang-ups and aircraft damage, is also required.

4.1.5 Engine models

Typical engine models are composed of a performance part (static) and a dynamic part. The performance of the simulated engine has a major effect on the speed of the aircraft, which is important in low-level navigation (timing). Reliable engine performance data are therefore required in the low-level high speed task.

Typical engine simulation methods for mission rehearsal applications must support such functions as start-up, relight, shut down, and should correctly simulate after-burner characteristics. Also, correct simulation of engine dynamics is important; thus correctly simulating surge and stall characteristics and polar moment of inertia effects on the own-ship body leads to higher fidelity simulation and thus to better simulator acceptance.

4.1.6 Systems models

For the electrical system, hydraulic power and fuel system, data are available as aircraft manufacturer's simulator data, wiring diagrams, system schematics, operator and maintenance manuals. Such data are normally adequate to enable realistic systems management simulation to be achieved.

For landing gear and brakes, the models reflect the dynamic behaviour of the aircraft between brakes off and roll out; and between touch down and parking (Barnes and Jaeger, 1985; Hogg et al, 1992). Such models cover the transition from aerodynamic flight to stiff undercarriage dynamics. Accurate ground handling, tyre and undercarriage models are difficult to derive. Setting up the data gathering experiments is itself difficult. In practice, assumptions are made to enable simplified models to be used. Given that the landing and take-off phases are not regarded as critical to the overall low altitude high speed mission rehearsal training objective, the use of models with the existing fidelity is probably satisfactory in this context.

4.1.7 Update rate

It may be necessary to run the aircraft and engine models at the same update rate as the actual on-board aircraft computers, for example 80 Hz. Current fast jet simulation models typically run at 50 or 60 Hz. Increasing this rate is not likely to increase the perceived fidelity or stability of the simulation. Given, however, the rapidly increasing power of simulation computers, there should be no technical problems in running the simulation models at up to 100 Hz.

4.1.8 Balance of required fidelity against simulation cost

Current models are perceived to be of sufficient fidelity for the low altitude high speed task and the need for any more detailed models, or the incorporation of higher order effects, has not been identified except for air-to-air refuelling where data for modelling wake effects etc could be improved. Availability of data is often not adequate, and it is a particular problem to obtain data of sufficient detail to simulate accurately flight manoeuvres outside the normal envelope or beyond flight envelope extremes.

4.2 Outside world environment (Avionics)

4.2.1 Simulated versus stimulated

The general issue, whether to simulate avionics systems or to stimulate actual aircraft black boxes, is discussed elsewhere in this report in Chapter 7. With regard to data requirements, the verification and validation data requirements remain much the same with either method. The requirement for design data availability is more of a concern when simulating or emulating actual avionics. Stimulation considerably lessens the amount of verification and validation testing, and as such inherently implies concurrency with the aircraft. The enhancement of industry standards for avionic system interfaces to allow the needs for operation within a simulator, would aid the adoption of stimulation techniques. Such an approach has been adopted in the civil aircraft field with the use of ARINC standards (eg see ARINC, 1986).

4.2.2 Fidelity

It is generally perceived that the fidelity currently achieved with simulator avionics is adequate, particularly when using stimulated avionic units.

4.2.3 Availability of source code for simulation

Much avionics and systems software, if available, is highly specific to the particular hardware environment in the aircraft, and again, because of supplier proprietary rights or export license restrictions, is often impossible to use directly in a simulator. However, avionic and airframe suppliers have in most cases put considerable effort into emulation and/or simulation packages for their own engineering purposes. Availability restrictions for these software packages are much more lenient. The situation on data supply would be eased if the procurement authority, in the procurement stage of either the airframe or avionic system, were effectively to incorporate the supply of data for simulation purposes into the contract. This is normal practice in the civil aviation field.

4.3 Malfunction & damage simulation

4.3.1 Requirement

There is a requirement to model malfunctions and damage to avionics equipment. To reduce the data problem it is recommended that the malfunctions to avionics be limited to those covered by the 'standard' manufacturer's diagnostics or Built-in-Test capability.

Such a restriction should not be significant for mission training and rehearsal. In many cases a simple total failure of the subsystem will be adequate. However, interaction with the other systems must be simulated correctly.

Damage to the airframe can be simulated by using "damage coefficients" which can be obtained from wind tunnel measurements. Probability calculations of the amount and type of damage done to the aircraft by nearby or direct hits of enemy fire can be simulated by using data from vulnerability models calculated off-line.

4.3.2 Data & model availability

It is generally hard enough to obtain data on a fully functioning aircraft or system: data for a damaged or malfunctioning aircraft or system are often not available in any form or are impossible to obtain. However the increasing use of computer aided design, with systems simulation and emulation being undertaken by the developers of the avionic system, should make it easier in principle for the avionic equipment manufacturers to produce such data. This is especially so if faults are restricted to those covered by the standard built-in test facilities.

To avoid the simulator designers "guessing" the consequences of a specific malfunction, and consequently leading to negative or dangerous training, there is a need to encourage manufacturers to release data.

5 BATTLE ENVIRONMENT/SCENARIO

5.1 Introduction

Given that source data are available, then it is possible to provide the simulator with the databases and libraries that allow a realistic portrayal of the static real-world environment to support the operational needs of high speed low-level flight. It is becoming increasingly possible to provide realistic simulation of the dynamic situation by the provision of multiple "intelligent" targets and players. Targets and other players can adapt their behaviour to correspond with their likely real-world responses to a given tactical situation. To provide this level of performance, it is necessary to store such information as combat manoeuvre rules, operational doctrine, performance capabilities, weapon/stores/countermeasure configurations etc. Such data are accessed by an intelligent knowledge-based system to guide the actions of the targets/players. Such systems are now available commercially and one (ITEMS) has been provided on the US Army Research Institute's STRATA simulator (Kurts and Gainer, 1992), as demonstrated to the Working Group on their visit to Fort Rucker.

5.2 Content

In general, there is no great problem in setting up databases and libraries, nor in gaining access to the data when running the simulator exercise, having overcome problems in acquiring source data (See 5.3 para 2). Issues relating to running simulations of specific sensors have largely been covered earlier in this chapter. Additional data that might be stored to support simulator mission management could include data for the intelligent knowledge-based systems, such as rules of engagement, doctrine and reaction responses. Such systems may need to access the terrain database as used by the visual system in order to move the target/player in an "intelligent" way over the terrain, or to determine lines-of-sight.

For ease of database management, it can be necessary to trade-off the detail required for the mission rehearsal task against the real-time capacity of the target simulation sub-systems. This means specifying limits to the capacity, such as the number of polygons, the number of emitters etc. To do this, a balance needs to be struck between such performance factors as sensor range, field of view, resolution and accuracy. For low-level missions, particular consideration needs to be given to terrain and cultural detail visibility (the height dimension is especially significant). To provide flying and navigation cues, adequate detectable features must be included. For attack phases, high detail (surface) targets with detectable features must also be provided. In the case of air targets (friendly and hostile), data needs to include threats and countermeasures, detectable features and signatures, as well as the knowledge rules for operational and reactive responses. The limitation on the number of active targets that can be visually displayed at one time has been discussed earlier in Section 3.2.3.3.

A good system is required to manage these various databases and allow rapid updating and correction; some changes may be required online during simulator operation, such as updating all the applicable databases if a target is destroyed or damaged. The required technical performance is achievable today, although each database tends to be put together separately. Future developments in database management systems, such as object-oriented databases, may allow a number

of individual databases to be combined and a more consistent set of database management tools to be used to input and update the stored data. The design of the database systems should include provision to use future data sources and allow for expansion of stored data. The systems should allow the user to maintain databases, not only to allow for updating of data but also for inputting classified data. In the latter respect, security aspects of the stored data need to be considered as part of the design.

5.3 Realism & accuracy

The perceived accuracy of databases depends on how well the databases and features have been correlated and checked. Correlation issues can be very significant and these are discussed in Section 6 of this Chapter. It is also important that the data used to plan the simulator mission are the same as are held in the simulator databases. For example, if actual operational maps are used for such planning purposes, it is possible that way-points are selected that are not present in the simulated terrain database. The intrinsic accuracy is limited to the accuracy and resolution of the source data such as is obtained from the US Defense Mapping Agency (DMA), cartographic, satellite and air/ground reconnaissance imagery, CAD, etc. Compromises on how much fine detail is extracted from these databases, in terms of cost of production and on-line storage capacity, may further limit accuracy and realism. These issues are covered in the sections dealing with specific sensor simulations.

Certain aspects of simulation may be limited by the availability of realistic or accurate data. This may be because it needs intelligence gathering of data, for example the flight characteristics of an enemy's missiles, or because the data have never been obtained, for example flight data for particular damage to an aircraft. As discussed in Section 3.2.4, there are limitations in the realism and accuracy of the weather models; while quite realistic simulations of many types of weather condition are possible, there are certain weather environments that cannot yet be realistically simulated, particularly related to 3-dimensional modelling of atmospheric structures.

It should be noted that the cost and maintenance of databases are reduced if particular mission corridors can be specified. This ensures that detailed modelling can be confined to such areas. Such consideration also allows the capabilities of the simulator to be optimised to the mission needs.

6 SENSOR CORRELATION

In attempting to provide visual and sensor scenarios that are consistent and coherent within themselves, as well as with each other, a number of correlation issues arise. These need to be addressed if the simulation mission objectives are not to be compromised. Problems can arise from deficiencies in the source data, the way the source data are transformed to the real-time database for the sensor 'IG', and the way the IG processes such data to produce the display.

6.1 Correlation between different sensors

Correlation between visual and sensor cues requires that the visual database matches the radar database. In general, source data are richer in content than can be processed and displayed by the various visual and sensor simulation devices. Thus, even when the same source data are used, different strategies are employed to filter the source data to produce the real-time database for the specific simulator IGs. For example, the low update rates for the radar simulation allow more objects to be displayed than on the visual system and with higher resolution. This means radar databases most often incorporate more of the original source data than do the corresponding visual database. Potentially key features may then appear on the radar and not on the visual system. If the strategy adopted to reduce this correlation problem were to restrict the radar simulation to the same detail as provided in the visual database, the radar scene presented to the aircrew would appear to be unnaturally sparse. To resolve some of these issues, known fix points that are typically used from the real world are repeated exactly in both visual and sensor database, ensuring that radar fixes will correlate with visual sightings.

The needs of the mission must be considered to obtain the most effective strategy for scene management within the various image generators. For example if the priority is terrain avoidance, high correlation between radar and visual scenes would be more important than high resolution radar images. The problems are, of course, compounded if the same source data are not used for all such simulators.

Even where the same level of filtering is used for the terrain, different IGs may use different algorithms to generate terrain polygons from the same gridded terrain data (DTED). It may be possible in the future to adopt a standard algorithm for this function. If not, it might be necessary to select suppliers who can provide this level of correlation.

The problem that the inter-visibility between the own-ship and a target or a threat may differ between different sensor simulators, or between a sensor and the visual simulator, is compounded at low level. For example, the target may be visible to the eye but not to the radar. This primarily arises from the differences in the terrain model as described above. Some problems can be overcome by making the visual the master and performing inter-visibility calculations within the visual system. In the longer term, five to ten years, techniques to support the use of interactive distributed simulators will provide more effective solutions to this problem - for example, by using an independent inter-visibility "environment" server accessed by all Image Generators (Latham, 1992).

6.2 Correlation across different data sources

If the same information regarding terrain or features is obtained for different IGs from different sources, then there is clearly potential for introducing significant correlation errors. For example, if the visual system derived its terrain elevation data from satellite stereo-pair photographs and the radar system used DTED, the construction of the basic terrain shell is likely to be quite different except for non-flat areas. Thus, for each category of data, a common source should be used.

While a common source of selected data, based on Project 2851 standards (see section 7.2), should be adopted for all the visual and sensor simulators, the raw data required to cover a particular area or object at all the required levels of detail may need to be obtained from different sources. For example: terrain elevation may be obtained in a gridded format from DTED, low resolution data may be derived from satellite photographs, higher resolution data on the area might be obtained from aerial photographs and further object detail obtained from normal photographs. It may be expected that, at least for the USA, the US DMA will reconcile any inconsistency in such data sources that they issue as SIF-compliant data (SIF, 1993) so as to ensure a coherent and consistent data package. Outside the USA, this work would have to be carried out by suitable agencies or by the simulator supplier.

6.3 Detailed data differences

6.3.1 Different resolutions and absolute accuracies

Computational differences in regard to numerical format and precision can result in systematic differences occurring in the positioning of terrain and features between different IGs. Also different systems may have different origin points for their databases (computational errors tend to grow with distance from the origin). Different systems may differ in how they map to a spheroidal earth model, such as the "World Geodetic System 1984 (WGS84)" (see WGS, 1984). These sources of correlation error should not be significant in modern high-end systems, but might need to be covered within the specification of such systems.

6.3.2 Different spectral ranges

Different satellites gather data using sensors sensitive to differing parts of the visible light and infra-red spectra. In general, there is no problem in combining such data; however, combining data obtained from light sensing devices and radar can give rise to problems as major features recorded by one may not be significant to the other.

6.3.3 Different collection times (feature movement, etc.)

It is obviously desirable to use data gathered within a short period of time to avoid problems due to major seasonal changes. In general, changes in photographic images caused by changes in general visibility, time-of-day, or photographic materials and processing can be handled by employing established image processing techniques.

6.4 Correlation between multiple networked simulators

There are many issues involved in achieving correlation between simulators that are connected over a network to engage in the same mission scenario. It is outside the scope of this report to consider the general problem. It is worth noting, however, that much R&D effort is being devoted to such networked simulation, under the title "Distributed Interactive Simulation" (see, for example, any DIS Workshop proceedings, (DIS, 1993) or (RAeS, 1994) and the latest Standard, IEEE, 1995). This work is likely to result in new techniques and standards that will also benefit correlation problems within a stand-alone simulator.

In regard to connecting two similar simulators on a local area network, for example to provide a manned wing-man, correlation issues - beside those on a stand-alone simulator - will mainly arise from the scene management strategies. With two simulators operating from a different view point, the scenes presented to the pilots could have different scene content, even though the simulators use the same image generator; the scene management must ensure that critical objects are

retained but without giving extra cues to the pilots as to target position etc.

7 SCENE DATABASE SUPPORT

7.1 Data availability

Geographic data for the generation of databases are typically issued by national defence mapping agencies. Currently, digitised terrain data are supplied in the Digital Land Mass System (DLMS) DTED format. Such data are security restricted, availability can be subject to export licenses and not all parts of the world are covered. An alternative source of terrain height data that has become available are stereo-pair satellite images. Photographs, for all areas of the world, and the software to extract the height information, are commercially available. As these photographs are also a source for photo-texture data, it is likely that this source will become the preferred one in the future. Cultural data, in digitised form, is supplied under DLMS as DFAD. For areas covered by DFAD, and where security restrictions allow its release, this is a useful form of data, permitting semi-automated processing for database generation. Where not available, or incomplete, other data sources must be used, such as maps, drawings and local photographs. Usually the required data are available, but can involve a time-consuming data gathering exercise, which has often to be repeated when simulators are produced by another supplier.

7.2 Project 2851

Project 2851 was the US DoD tri-service project that aimed to provide standard data bases and transformation software in support of training and mission rehearsal simulators (PRC, 1989; Cogman and Tomlinson, 1993). It addressed the issues of establishing a repository of data sources used to create visual and sensor simulators and providing data that are compatible for use on such simulators. By using a single source database, correlation problems between the visual, radar and other sensor simulations within a given mission simulator should be minimised.

An operational facility, the SDBF, Simulator Data Base Facility, was established in 1994 at Kirtland AFB, Albuquerque, NM in the USA, as an outcome of Project 2851, to provide databases for the US DoD. Once fully operating, this facility is expected to be fully occupied during its first years in building up a rich data source to satisfy the specific needs of US DoD programmes. It would not be in a position to provide source or transformed databases for areas of interest only to other NATO countries. While Project 2851 has provided standards for source data formats (SIF, 1993) and for transformed database formats (GTDB, 1992) to be used with US simulators, and these standards are recommended for adoption by other NATO countries, the USA cannot be expected to deliver actual databases outside the US DoD requirements.

The establishment of an organisation and facility to provide such data for NATO needs to be considered by the other NATO countries. At least in the short term, it may be that the simulator supplier (rather than a central agency) is asked to produce a database from the various sources, as at present. The supplier may then be asked to put such data into the military standard SIF/HDI format (SIF, 1993) and to make the data available to the procurement agency for reissue on future contracts.

Project 2851 provided a standard for holding the source data, and also one to support the interchange of data via the standard SSDB interchange format (SIF, 1993). The scope of this standard (Cogman and Tomlinson, 1993) covers the definition of terrain, culture features, targets and texture (including photo-texture) required to produce visual and sensor scene databases. It does not include atmosphere-related data such as cloud patterns, visibility and fog profiles. The SDBF repository will not hold versions of the terrain, objects etc. that may be changed as a result of the simulated mission, eg terrain with bomb craters or damaged objects, except in so far as they can be described in terms of various levels of detail. Dynamic changes will have to be developed by the device developer or by the user.

7.3 Preparation & maintenance

Considerable work is required to produce databases, particularly for sensor simulators. Project 2851 was largely initiated to reduce the cost of such work to the US DoD by avoiding duplication of effort. Changes in defence needs have led to increased emphasis on rapid deployment of multi-nation forces to disturbed areas of the world. This means that there must be an ability to produce databases relating to these areas at short notice to support mission rehearsal. Such databases must also be capable of quick and easy updating (maintenance) as intelligence data are received. Much work is being undertaken to meet these needs, with standards and tools being produced. While it may be possible to produce a usable database for a real-life mission rehearsal within forty-eight hours, it is considered unrealistic to expect that a large database of the quality that has come to be expected of training simulators (that

is, with the expected richness of detail and with the various anomalies and inconsistencies removed) will be produced that quickly. The use of standards and tools developed to support the rapid reaction capability will, however, greatly improve on the current productivity for databases.

To supply the amount of detail to provide adequate and realistic cues for high speed low level flight may involve supplementing available real-world data with synthesised data. To date this has been mainly a manual and interactive process. In the future this process may become more automated by using intelligent knowledge-based tools to reduce costs and time.

The set of tools to produce databases and subsequently to maintain them can be expected to be provided on powerful and ergonomic modelling work-stations. The tools can also be expected to be made available to users to produce and maintain their own databases. This is an area for continuing research and development.

7.4 Database re-use

Many of the re-use issues are being addressed by the Distributed Interactive Simulation programme (eg DIS, 1993) and by other work (see eg Cogman and Tomlinson, 1993). The following is perceived as the basic situation.

7.4.1 Re-use across different manufacturer's simulation equipment

For the foreseeable future, it is not likely that the run-time database generated by one supplier to execute on its equipment will also function directly on an equivalent system developed by another supplier. This is because, in its run-time form, a database has a format and content which reflect the specific architectural design of the equipment and its capabilities. However, if a standard, such as SIF/HDI (SIF, 1993), has been adopted for the source data, exchange of data at source level should be possible.

7.4.2 Re-use across different sensor simulation systems

Again, run-time database data format and content reflect the specific design and function of the equipment, so while they may be generated from the same source data, each needs to be regenerated for use with different sensor simulation systems. While the NVG and FLIR simulations may be run with the same database as used for daytime direct viewing visual simulation, there is benefit in tuning the visual database for night viewing applications. For example, changes in the balance between light points and surfaces to increase the number of light points, and optimising their distribution, can provide improved training - as was reported during discussions with the users of the UK Harrier GR Mk5/7 simulator.

8 CONCLUSIONS

This chapter has discussed database sources and libraries, with particular reference to scene generation, to represent both direct eye-ball viewing of an out-of-the-window scene and visual displays derived from electro-optical sensors.

The image generator (IG) determines the quality and appearance of the scene detail simulated, in terms of such elements as the number of objects, texture detail and modelling realism, while the display system sets the resolution with which the observer sees the generated scene. IG capability is influenced by many key factors, including polygon capacity, rendering performance, shading, texture and weather effects.

Current mission and training simulators now in use, such as the German Tornado and the UK Harrier GR Mk5/7 devices, while specifying the best available systems at the time of procurement, do not have visual systems that represent current state-of-the-art performance: they still have weaknesses in providing sufficient height and speed cues to fly visually at low level.

The procurement time for the development, build, integrate and test cycle for a complex simulator has been greater than the time between successive generations of image generators. This needs to be recognised in the procurement specification, by delaying the decision on choice of image generator until as late as possible.

The following sections draw conclusions relating to the seven objectives, identified in the Introduction to this chapter, that need to be met if data sources and libraries are adequately to serve the simulation needs of low altitude high speed training and mission rehearsal.

8.1 Sensor Scene Content

8.1.1 Visual Scene

The most demanding requirement for scene content is

for the primary visual system. This is seen by the pilot's eye and interpreted by the brain. Given the resolving power of the eye, there is no possibility of simulating the same scene content as can be observed in the real world. However, image generators are continuing to increase in power, and real-time database management systems are increasing in sophistication, such that major improvements are being made to their ability to portray greater scene content.

The studies on the German Air Force Tornado simulator showed that a large number of three-dimensional objects were needed to provide height cues for low-level flight.

The introduction of photo-texture has been a major factor in providing more realistic scenes. It is now probable that the latest generation of high-end visual systems, with colour photo-texture, more three-dimensional ground objects and an area-of-interest display, can provide sufficient scene content to enable manual high-speed flight to be accurately maintained at low level over undulating terrain. Research trials should be carried out to investigate this, to establish criteria for scene detail and to validate that the transfer of training is indeed sufficient.

Given careful planning of the database design to fit the mission training or rehearsal requirements, sufficient scene content should be available to allow navigational and target acquisition tasks to be performed. As display resolution is likely to remain less than eye resolution for some time (for technical and cost reasons), some target artifacts, such as artificial enlargement, may be needed to allow real-world acquisition ranges to be achieved. Improvements in static resolution need to be matched by reductions in dynamic degradations by increasing the up-date rate, using non-interlaced displays and reducing latency.

8.1.2 Other simulated sensors

It is considered that adequate scene content can be provided for the other, non-direct viewing, devices such as radar, FLIR etc. Different types of devices might require more emphasis on different aspects of the scene content: for example, providing more light points for NVG simulation. Whilst the scene content can appear realistic, the dynamic behaviour of FLIR scenes are difficult to model for the reasons given earlier in section 3.3.2; as stated there, modelling the interaction between objects is likely to be limited for some time to come.

8.2 Optimisation of databases

Techniques do now exist that allow databases to be optimised to match the performance of the image generator and display system for the mission. For real-time optimisation, scene management software controls the displayed scene to avoid overloading the image generator. By identifying the key cues for a mission, it is possible to design the database to suit the mission to ensure that mission-critical or other important objects are not removed from display by the scene management process.

The time and cost of producing a database, and its size, can be significantly reduced if it is possible to stipulate the likely areas or corridors that will be overflown for particular missions. In this way, it is also possible to optimise the capacity of the database (ie the number of polygons, objects and targets) by providing richer scenes over these areas and sparser scenes over areas unlikely to be traversed, or which are not important to the mission.

8.3 Modelling of own-ship aircraft performance

Mathematical models in current use are of adequate fidelity. The key issue is obtaining the data to produce correct instances of the model. There can be political issues and country-dependant export license restrictions on obtaining data when it exists. In addition, data are generally sparse over the entire simulation envelope. Correct modelling of the extremes of the envelope is especially important as pilots tend to use more envelope extremes in the simulator than in the actual aircraft. Care is necessary to avoid the consequent possibility of negative training if predicted or extrapolated data lead to an incorrect model. It is essential that data needs for simulation are considered as part of the aircraft flight trials - as is the practice in the civil aviation field. Providing good data for damaged aircraft or systems can also be difficult and the availability of such data should be considered when specifying simulator requirements.

Thus, where data are available, good fidelity modelling of the own-ship is possible to achieve the low altitude high speed mission requirements. Where such data are not available, the simulator performance, particularly at the envelope limits, must be validated in some way to prevent negative training, or the envelope must be constrained in some way.

8.4 Outside world environment (Avionics)

It is expected that there will be an increasing trend away from simulating avionic systems, because of the increasing use of software-based avionics. Simulation will be replaced either by stimulating actual aircraft hardware or, particularly in the case of expensive equipment, by emulating the equipment by re-using its software. The task of stimulation would be eased if equipment were designed with simulator use as one of the design requirements and if interfaces were to defined standards. Emulation is an attractive option as, by running aircraft software on simulator processors, keeping the system up-to-date with the aircraft is made easier. To achieve this, however, there is a need to encourage avionic manufacturers to release software to simulator manufacturers. Many of these issues were considered at a recent conference (Data, 1993).

8.5 Modelling of the battle environment/scenario

Provided source data for the relevant battle area are available, then it is possible to provide a realistic portrayal of the static environment. Recent, and continuing, developments are providing the means to produce realistic simulation of the dynamic situation; these provide for "intelligent" targets and semi-automated forces. The main restriction is on the number of independent moving targets that can be displayed by the visual system at any one time. Typically this is restricted to sixteen to thirty-two targets, and may not rise above one hundred for some time without special effort. However, given the speed of action in the high speed mission, a static "snap-shot" of the situation should be possible for most targets.

Provision of sufficient and adequate data to describe enemy threats and targets is the principal challenge in generating a mission environment.

Modelling of demanding weather conditions is limited by both visual system technology and adequate atmospheric models. No great improvement in this situation will occur unless specific research is conducted in this area.

8.6 Correlation of databases

Correlation of databases is a challenging issue. Correlation across sensors on a particular simulator is much easier than achieving correlation across a number of different simulators. The latter is the subject of substantial R&D activity in the context of distributed interactive simulation (DIS) systems. For the stand-alone simulator, provided the requirements for correlation of the various databases are clearly laid down in the specification, there should be no major problem that would limit the mission objectives.

If two simulators are to be linked, for example to provide a wing-man, the problem is still less severe than in the DIS situation. It should be possible to obtain satisfactory correlation in such an application, particularly if both are specified and procured with this application in mind.

The use of simulators in a fully distributed interactive simulation network is currently subject to major R&D efforts. The deployment of such systems to allow training of high-speed low-level flight is considered to be some years away. The discussion of the correlation issues associated with such systems is therefore considered to be outside the scope of this report.

The work from the various research and development activities in this field eg the DIS programme, stimulated by such applications as the US Close Combat Tactical Trainer (CCTT), a large-scale, networked, armoured-vehicle training system, should provide improved solutions and tools in the future.

8.7 Database preparation time

In the past, the cost of producing large databases for mission simulation has been considerable. The time to generate a database for a new area has also been a major concern, particularly where it has been required for mission rehearsal. These two aspects have received much attention in recent years and major advances are being achieved in both areas. A major initiative for time and cost reduction has been the US DoD Project 2851. This project has now successfully established a source data interchange format, SIF/HDI (see SIF, 1993).

Visual system vendors are enhancing their database production tools to automate the database generation processes further. Technical developments, such as the use of z-buffering, cut costs by reducing occulting problems. With the advent of photo-texture and the use of satellite images, the cost of producing databases can be reduced still more and the process speeded up. Given that the required data has been collected and put into the source data format, the production of run-time databases within a few days has been achieved to a standard suitable for mission rehearsal. For mission rehearsal in a real battle situation, aircrew priorities are such that they will accept a lower standard of database than would be acceptable in peace-time training. Thus,

while it may be possible to produce a useable database for a real-life mission rehearsal within forty-eight hours, it is considered unrealistic to expect that a large database of the quality that has become expected of training simulators will be produced that quickly. However, the use of standards and tools developed to support a rapid reaction capability will greatly improve on the current productivity for databases.

Collecting data for an appropriate geographic area still requires considerable effort. Terrain data derived from stereo-pair satellite images will become an increasingly important data source. Such data sources, combined with improved IG capabilities, should enable terrain to be portrayed to sufficient resolution to satisfy low-level flying requirements over most terrain types.

Research continues to be required, however, on tools to handle such data and to deal with image processing issues such as ensuring consistency in colour balance, and dealing with differences due to time of day and season of the year. Improvements are also required in methods for the production and modification of databases during the life-time of a simulator.

8.8 Database re-use

The principal activities in the production of databases are:

(a) Determining database requirements in terms of mission needs and system capabilities.

(b) Defining and collecting source data to meet the requirements.

(c) Generating the run-time database from the source data.

If the database to be used is to be optimised for the mission requirements, the first stage must always be conducted. Once this has been done, it is reasonable to investigate if a similar database has already been generated. If it has, and was developed for a compatible IG, then re-use is clearly possible. If, however, the database was developed for an incompatible IG, the run-time database cannot be directly re-used. One of the original Project 2851 objectives (see section 7.2) was to offer generic run-time databases that could be simply transformed to run on any compatible IG. So far this aim has not been achieved. With the diversity in IG implementations, and their evolving capabilities, this idea may not be practical for some time to come. However, by adopting the military standard (SIF/HDI) for the interchange of *source* data (SIF, 1993), it should be possible to re-use selected source data when constructing new databases for the same geographical area. Even if all the required data is not available, considerable cost saving should be achievable by re-use of such source data as is available.

While it will be some years before a rich source is available in SIF/HDI format from agencies such as is envisaged by Project 2851, it is now possible to specify that vendors put their source data into SIF/HDI format. By assigning data rights to the procurement authority, that authority can then make these data available to another vendor if that vendor is being required to produce a database including the same area.

Scene data re-use, interchange and correlation will all be assisted by adoption of the SIF data interchange format (SIF, 1993). NATO Nations may wish to consider how their respective data needs may be satisfied and coordinated.

9 RECOMMENDATIONS

Simulation of an effective environment for training and for practising low level high speed flying is hindered by a number of deficiencies in databases. The following recommendations are made to address these deficiencies.

9.1 Research into data requirements and utilisation.

Recommendation: Research aimed at a better understanding of the visual scene cueing requirements and the effective transfer of training achieved in simulators needs to be encouraged.

Comment: This will form a more objective base for specifying the data requirements of simulators and understanding their limitations within a total training package.

9.2 Collection of Aircraft and Avionic Equipment Data

Recommendation: Procurement authorities need to ensure that the data requirements for simulation are recognised at the time of ordering the actual aircraft, and that the contract embodies a suitable statement.

Comment: Simulator manufacturers are well able to define the data required for their simulation mathematical models. The provision of such data can then be stipulated at initial procurement, when

maximum leverage can be placed on the aircraft manufacturer. This is common practice in the civil airline field.

The adoption of standards for avionics equipment, and their interfacing, that include simulation requirements should be considered. This, too, has been achieved in the civil field.

9.3 Commercial and Political Issues in Release of Data

Recommendation: Procurement authorities need to recognise the problems that simulator manufacturers encounter in dealing with the commercial and political issues surrounding the acquisition of required data.

Comment: Problems would be eased if the data requirements were included in the purchase agreements, export licenses etc. for the actual aircraft. Procurement authorities should also educate the avionic suppliers that they are required, under appropriate commercial safeguards and payment terms, to make available data to the simulator manufacturer. This is well understood by the suppliers of avionics for civil aircraft. With the increasing cost of avionic systems, it is becoming advantageous to provide software simulation or emulation of aircraft black boxes. To help with this approach, the manufacturers need to be encouraged to make available the emulation and simulation packages that they will have developed to design the actual equipment.

9.4 Optimal Use of Data for Battle/Environment Scenarios

Recommendation: Simulator users should carry out requirements analyses to decide the specification of databases to suit the specific missions to be conducted. These databases should take into account the capabilities of the simulation systems and the database management characteristics of the visual and sensor simulators.

Comment: The technical capabilities of the visual and sensor simulator systems will necessarily limit the simulation fidelity of the environment scenario. What is important is to ensure that the scenario that is generated will be the best match between the mission being trained or rehearsed and the equipment capabilities. If this is not done, and no action is taken to select the appropriate features for particular missions or training objectives, then a non-selective database will be produced. This will result in sparse detail where high detail is required and include (at high cost) much peripheral data that are not utilised.

9.5 Technical Limitations in Simulator Sub-systems

Recommendation: Government defence departments should continue to support research to foster the development of improved visual systems.

Some topics meriting research and development identified in this chapter include:

(a) Scene management for Image Generators.
(b) Blending of photo-texture images.
(c) Display systems: increased resolution, non-interlaced displays, higher frame rates.
(d) Image Generators: more polygons, specular reflections, more dynamic targets.
(e) Transfer of training studies in the use of photo-texture for low-level flight.
(f) Better weather models.
(g) Forward Looking Infra Red (FLIR): modelling of dynamic interactions.
(h) Database generation, maintenance and management tools
(i) Database correlation across sensors and between networked simulators

Comment: Continuing support for research is necessary to ensure that more effective training and mission rehearsal simulators can be deployed in the future. Without such support, given the declining defence budgets and price-cutting competition, industry will not finance such defence-specific improvements to these simulation products.

The past twenty years have seen rapid and continuous technical developments in visual and sensor simulation. Visual systems, in particular, still fall well short of simulating the real-world. This report identifies that display resolution, polygon generation, low-level texture presentation and weather simulation are all areas where improvement is required. While further research is needed to determine what this "ideal" requirement is, it is likely to be more than is currently practical to achieve. To date, it has been the military requirements for simulation that have been the driving force behind the major advances in Image Generator and display technology.

9.6 Data Coherence, Correlation and Reuse

Recommendation: The procurement authority should ensure that the same data source is used by each of the various systems that make up the simulator. It is further

recommended that procurement specifications require that source data for visual and sensor simulator systems be supplied in the new standard SIF/HDI format defined in MIL-STD-1821 (SIF, 1993).

Comment: The use of common data sources will ensure consistency across the various simulation systems.

Recommendation: Each nation's procurement authority should have a policy for gathering, issuing and controlling such SIF/HDI data. Each nation should also assign responsibility for its application.

Recommendation: Where sensor correlation, or networked operation of two or more aircraft simulators, is required, the standards emerging from the US and European work on distributed interactive simulation (DIS) should be appropriately applied.

Comment: Adoption of DIS standards will help to reduce correlation and consistency problems.

9.7 Cost of Generating and Maintaining Databases

Recommendation: A careful analysis of the visual and sensor database requirements to meet the needs of mission simulation should be carried out to ensure that the costs of incorporating inappropriate features or gaming areas are avoided.

Comment: Many of the above recommendations will help in reducing the costs associated with producing databases and will assist in the re-use of data.

CHAPTER 6

HUMAN FACTORS

CONTENTS

1 SUMMARY

This chapter discusses some of the human factors issues associated with the use of simulation for low altitude, high speed mission training. It indicates that the application of new technology alone does not guarantee training effectiveness and hence improved operational performance. It proposes that effective training transfer can only be achieved through careful consideration of the human factors issues, and through an overall systems approach to training.

The use of operational training aircraft for mission training is restrictive due to externally imposed constraints and restrictions eg. restrictions on aircraft speed and altitudes, availability and use of electronic warfare. This leads to the proposition that the simulator and aircraft should be considered as complementary training devices. This is consistent with Roscoe et al (1980b) who considered that "..a training system has to be designed that incorporates vehicles, simulators, and other media and systems and is based on a thorough and systematical analysis of the goals and requirements". Therefore task analysis is of prime importance to achieve the desired level of transfer of training from the simulation to the operational aircraft. Simulation is best suited to the training of cognitive processes demanded by mission training and mission rehearsal.

2 TRAINING ANALYSIS

2.1 Introduction and Training Approach

The purpose of training is to produce improved operational performance in the real world. Flight simulators are frequently and successfully used for airline pilot training, however their use for low altitude high speed mission training and mission rehearsal is still under discussion. According to Roscoe et al. (1980b) training simulation has to be part of a systematically structured complete and overall training approach that results in defined gains. To determine the training goals and to quantify training gains requires task analysis. Before this can be carried out, the general characteristics and constraints of the flying task must be considered. Roessger et al. (1962) suggested three control levels: navigation, guidance, and stabilization. At the navigation level, the route to an intended goal is selected from the given network. At the guidance level, flight path and speed, are selected in consideration of the actual situation, regulations, etc. At the stabilization level, the vehicle is stabilized and adjusted within desired constraints.

Rasmussen (1983) distinguished three levels of trained behaviour: skill-based, rule-based and knowledge-based.

> The characteristic of skill-based behaviour is that it takes its course without conscious attention and that one cannot specify the information on which it is based. Examples are found with simple and frequent actions, e.g. aircraft stabilization.
>
> Rule-based behaviour diagnoses a situation on the basis of recognition of a combination of symptoms. Each situation is linked associatively to a set of "if-then" rules. Examples are the detection and identification of a threat and the design of an

offensive or defensive response.

Knowledge-based behaviour includes the conscious formulation of goals and the analysis and selection of plans of actions. A typical example is negotiating unknown situations, e.g. route planning in unfamiliar terrain.

The boundaries between these levels of behaviour and the levels of task are fluid. Each task level, navigation, guidance and stabilization, may interact with each level of trained behaviour. A rather inexperienced pilot in an aircraft with deficient dynamic characteristics may be in a situation to stabilize the aircraft with conscious attention, i.e. knowledge-based.

Since low level missions involve formations of mutually supportive aircraft, possibly operating with other air, land and sea forces, the behaviour of individuals interacting with each other is particularly important for mission training and rehearsal. When operating in groups, information is processed in parallel, therefore the communication structures and channels must be exercised and practised. This includes, of course, crew co-ordination. This is Klebelsberg's (1982) definition of behaviour in the social context.

Training is based on the human interest in gaining experience. Therefore trainees are manoeuvred into critical situations repeatedly and have many opportunities to generate mistakes. They pass through related consequences and train for appropriate decisions and actions. They operate as a multivariate system and synchronize their activities with the environment. Their actions are based on an internal model of the external environment of the information processing system. The effectiveness of this internal model is to some extent a result of training.

2.2 Training Goals

The aim of training is, therefore, to enhance and optimise the pilot's internal model of the external environment by a transfer of pilot activities to the rule- and knowledge-based levels of behaviour. The need for activity on the guidance and stabilization task levels is reduced by generating internal rules in order to be able to cope with infrequent situations in a standardized manner, or by training defective skills. This enables the crew to dedicate more activity to knowledge-based operations including both cockpit resource management issues and working effectively in large force packages or formations. In general successful training accelerates the process of gaining experience and minimizes the time scale for the creation of appropriate behavioral rules, and assures a required state of training. It remains of prime importance, however, that trainees remain aware of the consequences of their own actions. Excessive skill training may promote over competence, or uncritical sensations of safety. These attitudes are undesirable and should be repressed by the awareness that flying requires certain behaviour. Consequently, successful training is embedded into an overall framework that considers the long-term characteristics of changes towards desired attitudes.

2.3 Training Concept

A training concept forms a logical structure of requirements. They address selected goals from the overall spectrum of tasks. A promising approach considers training to be an interactive multiple level process (Brown et al., 1987). At the first level basic skill training takes place. Having acquired basic skills, individuals then fly, under certain restrictions, and gain experience in the second level. At the third level training takes place in order to generate behavioral rules. This process may be individually tailored to the aircrew's own particular requirements. Training task specifications lead to technical and operational specifications of training media.

Simulation has a number of inherent advantages as a training aid which makes it ideally suited as a training environment for aircrew. Many of these advantages involve the use of innovative procedures not available when using the operational equipment, or operational conditions which are only produced under special circumstances and at great expense, eg. Red Flag exercises.

The advantages of modern simulation include;

1. Simulation of 'war-like' environments, eg. electronic warfare, own and enemy weapon effects, large number of threats, mission rehearsal, large number of combatants.

2. Enhanced feedback systems, eg. quantitative measures of performance.

3. Additional artificial teaching features and procedures not possible in the real-world, eg. graphical representation of the cone of engagement of SAM sites, or the glide-slope in the visual scene, simulation freeze, reset and replay.

4. Simplified training environment, eg. improved aircraft handling qualities when learning mission aspects, no systems or aircraft limits to consider when learning combat tactics.

5. 'Un-restrictive' environment, eg. the ability to fly ultra low level, flight over towns, 'fire' a large number of missiles and other weapons.

6. The ability to practice and develop operations which are too dangerous to attempt in real life eg. emergency procedures, new tactics, flight control reversionary modes.

However, flight simulation also suffers from limitations which restrict its use. It cannot offer real world stresses, the fear of crashing, the effect of 'g' forces, and the real 'feel' of flying. Therefore it cannot satisfy an important aim of military training, that is to give the trainee increased confidence which comes from using the actual operational equipment under operational conditions. Another area of weakness of simulators is the often unrepresentative handling qualities of the simulator due to the reduced cueing environment of the simulator compared to the real world. This is particularly true for low altitude, high speed mission training, since one of the most important training outcomes is the learning of aircraft performance and handling qualities in the low altitude regime. These issues associated with simulation mean that there will always be the need to practice flying in the real aircraft. Indeed, mixing simulation with live training is likely to be the most cost effective use of these training devices.

Therefore the aircraft and simulator should be considered complementary training devices, each with its own advantages and disadvantages. A well designed training programme will be structured using both elements. It must be appreciated that to maximise training effectiveness, the simulator should not simply emulate the aircraft but rather it should be used as a training device which exploits its inherent advantages and mitigates its disadvantages.

The current generation of simulators do not support multi-force training. Research into distributed interactive simulation (DIS) and the development of autonomous intelligence algorithms of pilot behaviour needs to be encouraged. However, since these networks still come with the lack of risk, additional measures have to be considered, e.g., incentive systems, in order to encourage realistic behaviour.

The training concept hypothesis is that training results in gains. Therefore with any training, elaborate or simple, the key issue is validity of the training results. A positive transfer of learning into the real world has to be generated (Blaauw, 1982; Roscoe & Williges, 1980a), or training remains useless or may even become hazardous. How can transfer of training be determined?

The validity of the training has to be considered. This relates not just to the physical and dynamic validity of the simulator but to the goals of its use. The way in which it is operated, and its outcome in terms of performance improvements, including the motivation of the users (aircrew and instructors). According to Anastasi (1968), it seems helpful to distinguish three types of validity: construct, content, and criterion-related validity.

Construct validity refers to the concept underlying the training approach. It defines the extent to which training simulation is part of an overall training concept and the extent to which it is not. A logically structured overall training programme forms the frame into which training simulation is embedded. The function and gain of training simulation are well defined. These are the prerequisites for construct validity of training simulation.

Content validity means that the training situation provokes the kind of performance which it intends to improve. It says that training tasks have to be representative in order to provoke the kind of real-world performance addressed. Furthermore the measures, which may be of a different kind and far more extensive in a simulator, have to be representative scores of training performance. A frequently discussed type of content validity is face validity. This refers to what a training task appears to address superficially, not to what it actually trains. Face validity is not a desirable feature itself and should not be regarded as a substitute for objectively determined content validity. Nevertheless face validity improves the acceptance of a test, and motivation and cooperation of the trainee. But still, it cannot be assumed that improving the face validity of a test will improve its content validity.

Criterion-related validity is the only quantitative type of validity. It refers to results of a statistical relationship between training scores and related external criteria and correlations between both. It quantifies the transfer of training.

2.4 Training Tasks

To be successful, training should be based on relevant training tasks.To be properly representative is an important goal of the systematical analysis and classification of the flying task and a prerequisite of content validity. The analysis produces task specifications and measures, or scores, as criteria that quantify training performance, or success. Training task fidelity should never be taken for granted. The training of cognitive tasks of information processing is most promising for simulation. It addresses the generation of behavioral rules, which cover perception, recognition, identification, planning, problem solving and decision making processes. Examples of selected low altitude high speed flight training tasks are given in Chapter 2 on Operational Requirements, from which this is a selection:

- crew coordination
- communication
- look out strategies
- terrain masking
- tactical decisions
- pre and post checks
- navigation
- return to base

Additional issues may be considered. They refer to situations that may not be trained in the real world for operational, political or environmental reasons, or the training of which may be enhanced significantly. Examples from chapter 2 are summarized below:

- emergency procedures
- low level flight over populated areas
- low level flight below 1000 feet
- flight under controlled weather conditions
- controlled night operations
- controlled combat operations
- threat avoidance
- weapon use
- integrated interactive multi-force missions
- mission rehearsal.

Technical as well as operational requirements are derived from these tasks with the goal of creating and improving rule-based behaviour. Air traffic structure, acceptance within the population, noise abatement and the availability of different training systems, i.e., aircraft, simulators, tutorial systems and audio-visual media have to be considered. Aircraft based training remains of primary importance for psycho-motor skill training. Training scores offer additional possibilities for a wide-spread objective assessment of pilot performance. The use of simulators in the diagnosis as well as therapy of training deficits, in pilot selection and assessment eg. combat ready status should be considered.

2.5 Required Organizational Support

Effective training includes support of the user organization, such as on-line control and evaluation of ongoing training on the basis of the overall training concept. These activities ensure that desired attitude, behaviour, and knowledge are acquired. Successful training analysis recognizes the constraints of the user organisation. An area of particular concern is the simulator instructor manning policies. For mission training and other complex training tasks, the use of simulator instructors with current on-type operational experience aids trainee motivation and hence training effectiveness.

2.6 Transfer of Training

The quantification of transfer of training is based on representative measures of training success. These criteria of training effectiveness, or scores, are related to proficiency acquisition, retention of skills and to the transfer of training into the real situation. Representative tasks are carried out in the simulator and in the aircraft. Correlations between the scores from simulation and flight lead to statements about the transfer of training from simulation into the aircraft and allow for cost-benefit calculations of training simulation. Transfer of training also incorporates alternative training options and cost effectiveness calculations.

Ideally criterion-related validity ought to be established for each training task, however this would be too costly. Furthermore, the quantitative nature of correlations makes it impossible to produce real-world data from emergency situations. As a consequence, criterion-related validity may be restricted to carefully selected corner points of the overall spectrum of relevant tasks. Then qualitative, i.e., construct and content validity, measures have to be considered more carefully. It has been argued that there is no need for criterion-related validity if there is sufficient construct and content validity. This refers to the extent to which simulator results seem qualitatively correct when transferred to the real system (Hollnagel, 1981).

If a sophisticated training concept has been designed, construct validity may be assumed. How can content validity be assured? Human Factors expertise and past

experience have led to a set of technical requirements that are likely to improve the content validity of training results. They refer to assessments on the quality of the illusion that the real task is carried out in the real world, i.e., the trainee shall sense, perceive, integrate, judge and react to relevant stimuli. Stimuli-reaction patterns qualitatively similar to those of the real world have to be generated with the avoidance of cue-conflicts. An extensive list of criteria is given in chapter 3 on mission simulators for motion, outside forward view and auditory simulation as well as simulator networks.

3 SOME EXPERIENCES IN LOW ALTITUDE HIGH SPEED SIMULATION

3.1 Introduction

The ability to fly a modern fast jet aircraft at low altitudes and high speeds, whilst navigating and operating mission systems, requires highly trained air-crew with excellent psychomotor skills who are capable of sustaining high levels of concentration for extended periods. Initially to train and subsequently to maintain and hone these skills is an expensive and time-consuming exercise. Faced with declining training opportunities to use the aircraft, maintaining operational effectiveness of air-crew has become a major challenge for military planners. The application of simulation is sometimes envisaged as a ready-to-go training alternative. However, for the reasons discussed in this report, a flight simulator capable of providing effective support to low altitude, high speed, mission training and mission rehearsal is difficult to achieve. This section discusses some of the human factors issues associated with these devices and reviews the current experience from modern simulators such as the Tornado Low level Test Bed, the Harrier GR Mk5/7 simulator and the Alenia AMX simulator.

The most challenging aspect of a "full mission simulator" is how to provide all the necessary external stimuli to the pilot's visual, hearing, vestibular, tactile, proprioceptive and kinaesthetic senses. Vision is the primary sense utilized by pilots in controlling the aircraft. The pilot's perception of his surroundings is a key element in proper control of the aircraft. Once the pilot has assessed his situation, he can then use his other senses to make the necessary physical and mental adjustments. For example, during visual flight conditions and especially low level flight, it is very important that continuous attention be directed to the horizon, as well as to particular objects on the ground and in the air. Around 90% of the pilots attention in low altitude high speed flight is dedicated to the real-time view out of the cockpit, normally collimated to 3000 ft forward. The first requirement to be satisfied in the simulator therefore is a very detailed visual representation of the real world. This representation must provide the flight crew with all the necessities that accompany a specific flight mission as discussed in chapter 4.

Low level flight needs long and effective training to allow pilots and navigators to reach perfect individual concentration, precise target observation and recognition, good extrapolation from incomplete perceptions and the familiarization with the terrain all around the cockpit. To ensure effective training the simulation must provide the crew with sufficient cues to enable them to learn and practise these skills.

3.2 Simulation Fidelity

Most pilots nowadays encounter simulators during various stages of their training. The usefulness of these devices is hardly questioned during the initial training phases that aim to familiarize the pilot with the cockpit and its particular procedures. Interviews with pilots reveal that with more flying experience simulations become less acceptable. To overcome these concerns and to provide the experienced pilot with the attitude and motivation to act as an operational protagonist, rather than an abstract performer, improvements in the realism of the simulation continue to be sought. To achieve this high level of fidelity often means that sophisticated, leading edge, technology is employed. However little work has been done to quantify the degree of fidelity necessary to achieve target performance levels in training the various tasks. Further long term research should be encouraged in this area. However it is considered that fidelity in specific tasks needs to be higher for mission training than for mission rehearsal.

The cues required in a mission simulator may be classified as follows:

> INTERNAL ENVIRONMENT CUES - i.e. duplication of the appearance and feel of the operational equipment in the aircraft cockpit, e.g., the static and internal dynamic characteristics such as the size, shape, location, and colour of controls and displays,

> EXTERNAL ENVIRONMENT CUES - i.e. duplication of the external environment and motion

through that environment. The most obvious examples are motion from platforms or "g" seats and visual out-of-the-window cues.

OPERATIONAL ENVIRONMENT CUES - i.e. all active and interactive tactical/operational elements (EW, threats, targets, etc.) which generate attention, analysis, adaptation of the pilot.

The degree to which these equipment, environmental and operational environment cues match those of the aircraft is generally what is understood to be fidelity. However, a subtle distinction has to be made here between the real cues measured objectively (objective or engineering fidelity) and the cues the pilot subjectively experiences (perceptual fidelity) - see AGARD (1980).

Figure 6-1 shows that Operational Training Simulators have to posses all three types of cues for low level flight. The high level in the Equipment axis is today achievable without any particular difficulty. The other two axes represent the key point of the pilot's involvement in training simulation and effectiveness of pilot training.

The current generation of mission simulators provides good equipment and operational environment cues. Using aircraft for mission training provides good equipment and external environmental cues, yet often poor operational environment cues. This gives rise to the concept of the aircraft and simulator being complementary training devices.

Before a simulator can be used for training its validity for a given task must be determined. In the process of validating the device, fidelity can again become a major issue. Typically, the validation process consists of the following steps:

1 Pilots evaluate the feel and acceptability based on his concept of fidelity (perceptual fidelity).

2 Engineers measure the extent to which the simulator faithfully reproduces the vehicle dynamics (objective fidelity).

3 Psychologists measure how effective the simulator response characteristics are in providing adequate stimuli for the human operator to perform the chosen tasks.

4 Training specialists will validate the simulator against training objectives.

3.3 Aircrew Acceptance

A common concern expressed by pilots training on sophisticated simulators is often related to the general perception that they do not feel they are in the real aircraft and that simulators are a poor surrogate for real flying. These criticisms obviously have a negative impact on the training concept and on the ability of pilots to achieve and maintain combat ready status using the simulator. Pilot scepticism on the use of the simulator is related to different subjective criticisms. Specifically pilots often complain that they have to pay attention to the simulation, assume adaptations and avoid internal simulator distractions. For example, unlike the real world, there are no modifications of the lighting inside the simulator cockpit due to sun orientation, clouds and time of day.

However detailed and representative a simulator might be, if it fails to be accepted subjectively (face validity) as a training tool by the operators, i.e. aircrew and instructors, it does not meet the end to which it was designed. Good representation of aircraft models, visual and motion systems alone do not necessarily serve the purpose. A clearly defined concept of its potential use play an equally important part; it must be evident to aircrew what the benefits and merits of such a system are within an overall training or mission rehearsal approach.

A readily apparent difference between simulator and real flight is the absence of physical danger. Safety serves to reduce anxiety and influences the pilot's strategies for task execution. Coping with the mental perils of flight is an important component of pilot proficiency and stimulating such an environment, or at least its impact on performance, is one of the many challenges for the training community.

3.4 Simulation Sickness and Discomfort

If sickness occurs in the simulator, but not in the real world, it is often evidence of a limitation in the simulation of the environmental cues or a mismatch between the simulator cueing systems. The implications of simulation sickness are:

- Compromised training
- Decreased simulator utilisation
- Simulation after effects

In flight, through vestibular, somatic and kinaesthetic sensors, the aircrew can perceive aircraft motion 80-100 ms earlier than through vision. In simulated flight the

motion information perceived by the human motion sensory mechanisms may be in conflict with expected inputs stored in a neural memory generated by experience. It is this conflict that can lead to the general feeling of nausea which is often associated with simulation sickness. Therefore to reduce the probability of simulation sickness, correctly harmonised platform motion cues are required. Poorly harmonised motion cues will lead to increased occurrences of simulation sickness. The total absence of motion cues may also lead to simulation sickness.

3.5 Simulation and Flight Safety

Inadequate and inappropriate simulation can produce negative transfer of training under some circumstances. Negative transfer of training from flight simulators is extremely rare, Orlansky and Chatelier (1983) reported the results of 34 different transfer of training studies of flight training (including, basic training, ASW manoeuvres, instrument flight, and multi-engine transition). The results showed that the training effectiveness ratios (TERs) varied form -0.4 to 1.9, with a median value of 0.48 and that only one simulator displayed negative training. A more recent study of 22 simulators by Fletcher and Orlansky (1989) indicated that the average TER was 0.67, and none of the simulators reported negative transfer. This result indicates that for the simulators tested that on average 1 hour in the simulator was equivalent to 40 minutes in the aircraft.

Simulation is not real flight, but it has to be as representative as necessary. If any simplifications or modifications compared to the real aircraft have to be made they should never compromise flight safety. In this context, topics to be taken into account are:

- Induced Simulation Sickness after effects
- The lack of an adrenalin-mechanism
- Fidelity of the mathematical model of the aircraft.

Induced Simulation Sickness is related to the after effects or post-exposure effects falling into two categories, those that are a continuation of the signs and symptoms of motion sickness and those that are manifest only after leaving the simulator, notably ataxia and "flash backs" in the visual or vestibular/proprioceptive sensory modalities. Negative transfer of training and delayed-onset symptoms, such as "flash backs" or disorientation, may have significant safety implications.

The lack of adrenalin is due to the lack of a risk environment in the simulator that involves the physical, psychic or mental fatigue of the pilot. In the aircraft this kind of stress releases the Adrenalin-Mechanism related to a higher heart rate, higher blood pressure, higher oxygen consumption and other physiological aspects. Some particular condition could give no sickness symptoms on the simulator while in real flight they are expected, therefore the simulated mission is performed in unrepresentative stress condition. This problem could represent a benefit for training tasks, while the pilot is learning the necessary skills, however it could at the same time be a danger for real flight.

As part of the German Tornado simulator evaluation, the behaviour of the crew in real flight (low-level flying in Goose Bay) and in the simulator was evaluated by an aviation medicine working group through questionnaires, interviews and crew heart rates measurements (Welsch,1992) The mission profile evaluated in real flight and in the simulator was: take-off - rapid descent - low level flight (50 - 250 ft) - air-to-ground attack - air-to-air intercept - and landing. Apart from differences under true physical stress (g-load), hardly any differences between real and simulated mission heart rate could be identified. The heart rate at low level flight was almost the same in the real flight as in the simulator. The most significant difference occurred during an actual emergency. Here the heart rate of the crew in the real aircraft increased and remained at an elevated level even after the landing. Similar occurrences of increased heart rate during crash landings in the simulator were never observed. The essential findings are: Heart rate may serve as a measurable indicator of aircrew task identification and involvement. During those parts of the mission which are particularly demanding in the simulator, the increase in the heart rate is not so much a response to low-level flight but rather to physical strain, visual, and vestibular stimuli under particular mental stress conditions. The mental workload of aircrew in the Tornado Simulator was very similar to that of the actual aircraft. This however, must not and does not allow by itself conclusions of positive or negative transfer effects between simulator and aircraft. Psychological crew conditions are influenced by the confidence in the reliability of the weapon system, the aircraft handling qualities, the experience gained from actual flying hours and even the simple pleasure of flying.

Fidelity of the mathematical model is important but is sometimes limited by available data of the aircraft. Full effectiveness and safety training at simulator facilities is possible only if the simulation is an adequate

representation of the aircraft throughout the whole flight-envelope. Therefore to avoid false impression of safety when operating at the edge of the performance envelope, exact simulation of the complex structure of the aircraft's aerodynamic, performance, handling etc is indispensable.

3.6 Coping with the "real operational" environment.

The human brain collects pertinent external data and changes this data into recognizable information. When the information requires a response or reaction, we must then invoke the brain's decision making function. The function will extrapolate and filter the given information and generate a list of logical responses or reactions. Then, by choosing from this list, we make a decision. Whether the decision is simple or difficult, is determined by the complexity of the input information and by the amount of related knowledge and experience one has. What might be a very simple routine decision for an experienced pilot could be a very difficult one for a pilot with little or no experience in this area.

Ultimately military training on aircraft AND simulators should be considered under this rationale. The saying "You fight like you train, therefore train like you intend to fight" still holds true. Mission training for specific operational missions, ie. mission rehearsal, places additional demands on the simulation. This not only means a high fidelity aircraft simulation model, but also requires that the external world environment is recreated to provide the proper and necessary cues. In particular the external real world as seen by the aircraft sensors must be simulated, and this must include simulation of the Electronic Warfare (EW) environment, the visual and infra-red images from applicable sensors and tactical data link networks (e.g. JTIDS) In addition, particular care should be given to recreate a tactical environment similar to the operational one. This means the inclusion in the simulation of an adequate number of cooperating and opposing forces (aircraft, ground and naval vehicles, AAA, SAM sites, etc.), each capable of independent behaviour either automatically predetermined, piloted by human instructors, or driven by appropriate interactive simulation.

3.7 Lessons learned from the Tornado Simulator (VTS)

Most of the information collected in this section was derived from evaluation of the Tornado Simulator Low Level Test Bed of the German Air Force. The aim of the programme was to define the low altitude high speed training needs a simulator could meet with current and future technology. This type of programme is unique and offered important lessons for the future development of simulation in this area. A brief technical description of the Tornado LLTB is given in chapter 3.

According to the German Air Force Staff

> "Training hours spent on the simulator cannot be used as a substitute for practical flying operations, but are a complementary extension of flying training. Simulator hours provide a completely new quality of flying training".

3.7.1 The experimental programme

The experimental programme was divided into test and field trial phases.

During the Test Phase :

* 6 mission each were flown by 43 crews (Air Force and Navy);
* of the 258 missions, results from 254 were evaluated using objective (i.e. recorded) and subjective data (questionnaires).

During the field trial phase:

* 64 air force and 31 naval air missions were flown by 16 air force and 9 naval crews;
* evaluation by questionnaires.

3.7.2 Evaluation

The aircrew were asked, in general, to make direct comparison between the simulator and actual aircraft flight and, not surprisingly, few rated the simulator as close to the aircraft in low level flying.

Simulator reliability had a significant impact on the evaluation. Mission interruption took place quite often as a result of system errors and the programme schedule required that resolving system errors had a relatively low priority, compared to completing a statistically significant number of missions. Failures of this nature generally resulted in negative crew comment, especially if such a failure resulted in a mission objective not being achieved.

Problems arose from incorrect alignment or fitting of helmets, especially early on in the evaluation, when the crew involved were less experienced. These problems resulted in some very negative first impressions being

given of the simulator. Such first impressions were difficult to reverse. The change in experimental procedure later in the program, which introduced the eye tracker at a later stage, reduced the incidence of these set up problems.

One factor which the experimental procedure could not prevent influencing was that associated with crews arriving for their test flights already primed with information and perceptions gathered, third-hand, possibly from other crews. This information may or may not have been accurate. It was certainly evident that despite the very objective briefings given to all crews that there were a number of cases where crew comment indicated a poor understanding of the system being evaluated.

The missions themselves were quite demanding of each crew member and required a level of effort much higher than found in previous simulator training missions. The crews were called upon to fly aggressively, at very low level, after only a relatively short time in the simulator. As similar aircraft missions were not part of the evaluation, a comparative judgement of the level of effort is difficult to make. A number of mission-related crashes were the result of flight at extremely low level. Indeed, on some occasions crews agreed that they would not have attempted such manoeuvres in the actual aircraft. What does seem to be clear from observation of the evaluation process is that the LLTB simulator, despite its shortcomings, appeared to involve the aircrew very heavily in the tasks and missions which they were assigned.

Although many criticisms were made of the visual system, the platform motion system was generally well received by crews and was felt to give a more realistic simulation environment. It is to be expected that the platform motion movements would assist the pilot as the cues provide rapid feedback of the effect of stick movement which can aid in controlling flight parameters. However, the expected effect of motion on the WSO and the effect of atmospheric disturbance motion on the pilot would be to increase the task difficulty and hence the workload. The general crew appreciation of the platform motion therefore represents a belief that it is better to train in an environment closer to the aircraft rather than one in which the task is artificially simpler due to the absence of mission stress.

Despite the aggressive manoeuvring called for in the missions comparatively few crews experienced the phenomenon of simulator sickness, certainly less than were originally expected by the German flight medical experts. In other high performance aircraft simulators, simulator sickness can often affect a high proportion of crews using the device, especially in aggressive manoeuvring situations. The LLTB appeared to be significantly ahead of other devices in this regard. In order to facilitate eventual data analysis, the missions were standardized to a higher degree than they would be in practice. This resulted in workload levels which were, in many areas, higher than those experienced in the actual aircraft.

Generally speaking the navigators had more problems than pilots with the display system, but the opposite is true where sickness symptoms were concerned. One reason for this is traced to the fact that navigators are used to being passively moved around without being actively involved in the handling of the aircraft. Pilots in the other hand perceive a mismatch of cues and lack of fidelity differently and compare their cues with their real world experience. Additionally on Tornado the navigator's attention is more directed inside the cockpit than the pilot's.

Post-flight interviews highlighted the frequency of the encountered simulation sickness symptoms.

- Only two pilots had to abort their mission because of serious sickness symptoms (One of the two was later identified as a cross-eye problem of one crew member)

- Simulation sickness symptoms persisted after landing on about 13% of pilots and 8% of navigators

- The symptoms decreased after some test flights as a phenomenon of auto-adaptation

- The simulation sickness symptoms were much more evident during the mission phase which included HI-LO transition and the LO-LO penetration up to the target.

Missions were generally performed well by all the crews involved with very evident team work being demonstrated between pilot and WSO. Of course, in the in-service OFTSs, the WSO has no visual scene and thus his greater involvement in the mission in the LLTB was to be expected, as was the generally more favourable comment received from WSOs in the questionnaires. This evidence of a capability to improve the teamwork between crew members represents a significant endorsement of the system's merits.

4 CONCLUSIONS

A methodological approach addressing the overall training concept is the prerequisite for simulator based training. The primary requirement for simulation is to provide positive transfer of training from simulation to the operational environment. Simulator networks may enhance training in the social context. Human factors requirements address the fidelity of training tasks and measures. Since simulation is not a substitute for live training, the cost effectiveness of training simulation must be based on the measurement and amount of the transfer of training achieved. Weighing the arguments for aircraft training against those for simulator training it becomes apparent that both have a contribution to make. Training in aircraft and simulators should be considered as complementary, as both are subject to different limitations. The definition of the best mix of simulation and aircraft training will be facilitated by a continuous process of training needs analysis.

The relation and the interaction between the pilot and the low level flight simulator have been described in this paper, based on experience of the Tornado flight simulator of the German Air Force, the Harrier GR5 flight simulator of the RAF, and partially the Alenia AMX flight simulator.

An effective and sophisticated low level flight simulator is a very difficult system to develop. The difficulty lies in the development of all the visual and motion cues that are critical to sustain low level flight. With current technology, this simulation is very close to the real flight. Improvements still need to be made with databases,, aircraft mathematical model and operational environments in order to achieve the best simulation training effectiveness. It is a shared belief that in order to maintain and improve military aircrew's efficiency in low level flight missions, integrated flight simulation in combination with real flight is essential. The following picture summarize this concept. The use of flight simulation integrated with the real flight in the training concept, gives to the aircrew the possibility to reach a superior level than the standard in less time and with better quality.

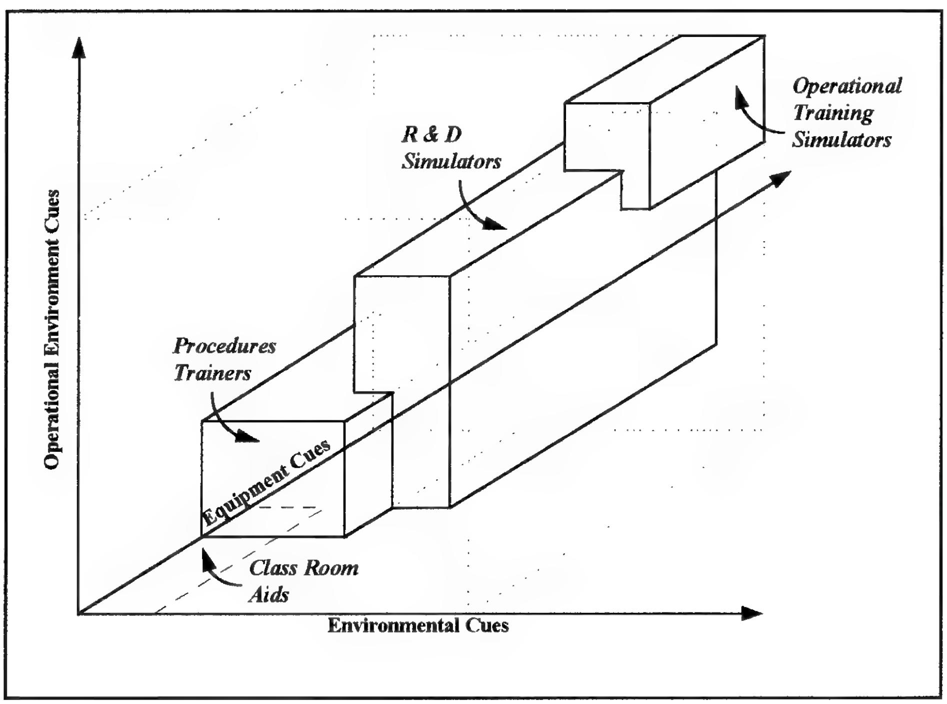

Figure 6-1 The complexity of operational training simulators

CHAPTER 7

INTEGRATED MISSION SYSTEMS

CONTENTS

1 INTRODUCTION

Modern tactical aircraft contain a number of complex cockpit avionic systems which aircrew must use to perform the intended mission. The representation of these systems in a simulator presents particular problems to the simulator designer. The simulator, while it is intended to mimic the actual crew environment as accurately as possible, differs from the aircraft in a number of ways which can affect the performance of these avionic systems. The ability to freeze the simulator during a mission is an obvious case, as is the ability to reposition. In fact there are over twenty ways in which a simulator environment can subject aircraft avionics to unexpected states (ARINC, 1986). Such conditions can cause the equipment to fail or produce erroneous outputs, such as incorrect positions and velocities.

If avionic systems are simulated in software, rather than stimulated, the problem of dealing with the simulator environment is eliminated. However it is replaced with an equally challenging problem of providing an adequate representation of the system in the simulator without the actual aircraft hardware. The choice, whether to simulate or stimulate, is generally dependant on the complexity and the development status of the system in question, its cost and availability and the number of applications expected for any resulting simulation model. Thus it is usual to find that the aircraft mission computer is a stimulated aircraft part, while the autopilot is a simulated system.

A further option is emulation. These three techniques are briefly defined as follows (see Hutchinson, 1993):

> **simulation:** modelling the functionality of the system to enable training to be achieved under normal and abnormal conditions;
>
> **stimulation:** use of actual hardware, and its embedded software, driven with appropriate inputs from the simulator;
>
> **emulation:** re-hosting of software from the target system, replacing any hardware-specific functions with additional software.

When aircraft avionics are used in the simulator, unique conditions are often supported using test ports which allow direct access to the state equations controlling the avionics processing or even by the incorporation, by the avionic system manufacturer, of simulator-specific software which is activated only while in the simulator.

This chapter discusses the issues associated with the simulation, stimulation or emulation of the various mission computers, navigation computers, weapons computers and associated display systems, typically found in today's combat aircraft, in order to support the goal of full mission training in a flight simulator. Several papers (notably papers 2, 3, 6) included in a recent conference (Data, 1993) provide further useful discussion of the issues concerned with the choice of simulation, stimulation or emulation.

This chapter describes the problems encountered in a typical tactical simulator, discusses the current situation in the commercial airliner simulation environment and offers conclusions towards improving the compatibility of tactical avionics and flight simulators.

2 THE PROBLEM

2.1 Choice of approach

The first issue confronting the designer of the training simulator is whether to simulate or stimulate the avionics system in question. Frequently, the choice is made by the procurement authority which mandates a solution, that the equipment be stimulated. In an unconstrained case, however, the decision to simulate or

stimulate is taken based upon an analysis of the cost and technical risk of the two options.

A decision to simulate would typically result if all or a majority of the factors listed below were true.

(a) Sufficient simulation design data was available and the resultant simulation fidelity would be sufficient to meet the training requirement.

(b) The actual equipment had significant cost.

(c) The actual equipment was mature in its design cycle, ie few or no changes were expected.

(d) The simulation solution could be reused a significant number of times. (Note: the number of times deemed significant is dependant on the cost of the actual equipment.)

(e) The cost to simulate was lower than the cost to stimulate (e.g. if several simulators for the same aircraft are being procured).

Typically the results of this type of analysis or customer preference determine that a stimulation approach will be employed. Indeed, this is generally the case for aircraft mission computers and display systems.

Increasingly nowadays a third option is emerging, emulation of the actual equipment by running the same software in lower cost commercial computer systems, often alongside the rest of the simulation software.

2.2 Simulation Issues

Where sufficient data is available to support the software design requirements and when the equipment to be simulated is relatively mature, simulation provides a good solution to the problem of providing training on the integrated mission systems. In particular, the simulation software can be made fully compatible with the unique requirements to deliver training, such that simulator features such as freezes, repositions, weapons reload, etc, (ARINC, 1986) can be accommodated within the simulation software. Similarly system malfunctions, to support training of emergency procedures, can be fully supported. Modification and updates only require software changes, but the implementation of such changes in the simulator may lag the installation in the aircraft by many months, leading to wrong training.

A particular requirement of tactical training is often the need to support record and playback and snapshots, to allow trainee actions to be reviewed. These are well supported by a simulation solution.

2.3 Stimulation Issues

Where stimulation is the chosen solution, the system will reproduce the correct functional characteristics and built-in-test functions, and system updates should be straightforward, but other problems can occur. These problems are generally related to mating the avionics equipment to the simulator and its interfaces and also achieving reasonable response from the equipment in the face of the simulator specific functions described in section 2.2 above. There may also be constraints on implementing the full range of malfunctions desirable for training purposes.

2.3.1 Simulator Interfacing

Interfacing aircraft equipment in a simulator involves the simulator manufacturer in an avionics integration task which is in many respects similar to that which the aircraft manufacturer faces when integrating the equipment into the actual aircraft. The first and most important requirement, therefore, is adequate data to allow this integration to occur. This first point has often been a significant hurdle, with aircraft and avionics manufacturers unwilling or unable to supply the necessary data so the simulator manufacturer must feel his way through the integration process.

The special requirements of the simulator environment make it essential that the functions and internal algorithms employed in the aircraft avionics being integrated are well understood so that trouble shooting of system anomalies can be performed. For example, a typical problem occurring during integration of a mission computer system may be that the steering outputs to the HUD are oscillatory. Many possible causes could be at the root of this problem, including software errors in the mission computer (a common problem when the avionics system is still undergoing change), some error in the simulated data input, data not refreshed at a high enough rate, excessive latency in the interface. Detailed understanding is required to resolve these types of issues.

The commercial airlines and simulator manufacturers have developed standards to control the integration of avionics equipment in simulators. Pressure from the airlines, with their considerable marketplace influence,

has led to most avionics suppliers and aircraft manufacturers conforming to the standards defined by ARINC 610 (ARINC, 1986). The military user is in a position similarly to influence the manufacturers of military aircraft and avionics. The development of a standard defined under the auspices of an AGARD study would aid in the attainment of this goal.

2.3.2 Simulator Functions

As discussed above, the simulator training environment places demands upon the avionics equipment, that it be able to accommodate, in an uneventful fashion, so-called simulator functions, such as total freeze, reposition, etc (ARINC, 1986). Mission computer systems tend, typically, to perform many navigation calculations involving various state equations, integration algorithms and the like. Without special treatment, a simulator position freeze, for example, will not be recognised by the computer and a position error will result. The effects of such situations can range from the relatively benign, such as a position error developing, to catastrophic, such as an autopilot hardover condition or system disengagement.

It can be argued, with some validity, that to support full mission training and mission rehearsal the simulator should be used as though it was an aircraft, without the use of any special conditions. However, simulators are inevitably used for many tasks other than full mission rehearsal and for these tasks the ability to make efficient use of simulator time is of great importance. Thus there is significant demand for the support of simulator specific functions such as weapons reload, record and playback, or snapshot recall.

Here again ARINC 610 (ARINC, 1986) may provide a guide to the development of a similar military standard. ARINC 610 defines in detail the protocols for a wide range of simulator functions which avionics systems manufacturers are required to support. Many of the functions discussed in this standard are not necessary for military training applications. Equally, many military specific requirements, such as weapons reload, are not defined in the ARINC standard. (Note that the standard is currently under revision to ARINC 610A.)

2.4 Emulation Issues

Emulation of the avionics is an attempt to overcome the shortcomings discussed in section 2.3 above while maintaining a high fidelity result. Essentially, the technique involves executing the same avionics system software, rehosted in the simulation host computer, as would be run in the actual system. In theory, this results in simulator performance which is identical to the aircraft case and allows for the concurrent upgrade of the simulator and the real avionics. (Military simulators are often criticised for not being at the same revision level as the aircraft.)

In practice, this desired result is somewhat more difficult to achieve. While the simulator can certainly be made able to run the same software as executes in the actual avionics, this does not necessarily result in an identical performance being achieved. The avionics performance is dependant on many aspects of the hardware configuration, such as the Input/Output (I/O) structure and bandwidth, memory access times, and databus loading. To achieve equivalent performance, careful matching of these characteristics may also be required. Indeed, it may be necessary to create simulator-specific I/O drivers to achieve the same resulting system performance. There may also be non-technical difficulties: if the avionics manufacturer is unable (due to national export restrictions) or unwilling to release the avionics software, emulation would be precluded.

Aircraft software also needs to be changed to accommodate simulator-specific functions. Thus, unless very careful partitioning of the software elements is maintained, emulation may not be the saviour that it may outwardly appear.

Here again there is need for leadership to establish standards that can be used to control the development of future solutions. AGARD provides a natural focus for such a standards development activity.

3 CONCLUSIONS AND RECOMMENDATIONS

The discussion has shown that choice of method is dependant on a number of factors including cost of equipment and availability of data. The most significant factor is the training requirement, as this influences the need for specific simulator functions such as simulator repositions and the like, which can often only be fully supported via simulation or emulation.

The incorporation of adequate fidelity of representation of system functions in a simulator is now a major and growing issue and generally exceeds in complexity the achievement of adequate fidelity in the simulation of flying qualities.

The world of civil aviation has prepared a number of documents to assist in the achievement of successful simulators for training eg IQTG (1992), IATA (1993), ARINC (1986). The military world has no equivalent documents. AGARD could be instrumental in the generation of appropriate documents for military simulators, building on the civil experiences, including the development of an ARINC 610-like standard for military simulators which could be used to ensure new avionics systems have embedded capability to support the implementation of simulator specific functions.

CHAPTER 8

CONCLUSIONS

CONTENTS

1 REVIEW

Effective piloted simulation of low altitude, high speed flight for mission training and rehearsal poses significant challenges to current and evolving simulation technology. Improved capability would have major operational, political and cost benefits. This Working Group report has reviewed the current state-of-the-art and potential of piloted simulation in this field and the improvements that are in prospect.

The report contains much general information about mission tasks, mission simulation and simulation technology which it is hoped will be of interest to many people involved in the acquisition and exploitation of piloted flight simulators. The content is deliberately not limited merely to the specific cueing issues of simulating high speed flight close to the ground.

The report has attempted to address such questions as:

(1) where does today's simulation technology fall short in providing what is required to meet the training objectives?

(2) what are the technological obstacles to achieving what is needed?

(3) what kinds of research programmes might overcome the technical obstacles?

The report has concentrated on simulation technology as a contribution to decisions on training requirements and equipment specification; it has not attempted to discuss issues of training policy. It is vital, however, that the aims of simulation are properly defined and that the role of simulation is considered in the context of a total training system.

The information in the report is based on the knowledge and experience of the Working Group members. These national experts, from six NATO nations, were drawn from the simulation industry, the aircraft industry, research organisations and users, including three Air Force pilots with appropriate operational experience. The Working Group has also been fortunate in having access to two of the latest mission simulators, the Tornado Low Level Test Bed Simulator (VTS) in Germany and the Harrier GR Mk5/7 Mission Simulator in the UK. These simulators use different types of image generator and area-of-interest display technology. The lessons learned from these simulators, and the evaluation of the experimental results from the German Tornado Low Level Test Bed Simulator, in particular, have been most helpful.

While this report has naturally concentrated on simulation of fast jet aircraft, it has not ignored helicopters: indeed, the Working Group visited the US Army training centre at Fort Rucker, Alabama to see the Apache Combat Mission Simulator. Many of the simulation technology issues are similar: some display systems in helicopter simulators achieve a wide field of view by using the same technology as in the German Tornado test-bed. Image generators, too, need to be very capable, to produce adequate terrain modelling and scene detail. So overall this review of simulation technology is also potentially relevant to helicopters, even though the operational and training requirements are different between helicopters and fast jets.

This chapter summarises the broad conclusions in relation to the aims of the Working Group identified in

Chapter 1. More detailed information is contained in the individual chapters.

2 BROAD CONCLUSIONS

The Working Group's broad conclusions are:

- training simulators and the aircraft must be viewed as complementary components in the total training package; neither simulators nor the aircraft in isolation can support the training necessary to enable pilots to be most effective in low level missions;

- low altitude flight is the most difficult phase of fast-jet operations to simulate in terms of the cues needed by the pilot;

- full mission simulation is, in a sense, more complex than the aircraft itself (at least in software terms), because a simulator has to provide a simulation of the aircraft, its weapons and its systems and also of the external natural and mission environments;

- simulation of the outside world visual scene, both visually and to represent sensors, is the critical technology, though image generators are now becoming available capable of generating the terrain and three dimensional features required for low level flight;

- there are important procurement issues which need to be addressed, particularly concerned with the provision of aircraft and systems data and with decisions on the visual system to be employed.

2.1 Role of simulators and aircraft in low altitude high speed mission training and rehearsal

Simulators and the aircraft must be viewed as complementary devices in the total training package. Neither in isolation can support the necessary training. Both aircraft and simulators have strengths and weaknesses as training devices, but together they enable pilots to be most effective in low altitude high speed mission training and rehearsal.

Simulators are not properly recognised as a component of growing importance in achieving operational effectiveness of the actual aircraft as a weapon system.

Tasks where simulation is of particular value, because they cannot effectively be carried out in real aircraft for operational, environmental or political reasons, include:

- mission rehearsal
- training in a realistic threat environment (eg with electronic warfare, surface-to-air missiles, and hostile aircraft)
- emergency procedures including battle damage
- activities requiring control of the external environment (weather, deliberate obscuration)
- low altitude flying training at less than 250 ft
- low flying over urban areas (day and night)
- assessment of crew co-ordination and performance
- integrated mission exercises and rehearsal (multi-force, with AWACS, fighters, large ground forces) at affordable cost
- weapon release, especially versus reactive targets
- provision of a secure (and safe) environment to develop tactics
- selection, and repetition, of task elements

Several of these mission training tasks cannot be trained in live flight under any circumstances, especially those that are closest to mission rehearsal. Some of the others are possible, at a price (by Red Flag, for example) but cost, environmental impact and practicality are the main drivers to suggest simulation is the most appropriate method.

Tasks where simulation supplements flight include most other mission tasks, recognising that simulation offers aircrew the opportunity to practise, and perfect, in selected and controlled situations, procedures necessary to ensure mission effectiveness.

Beyond the value of simulation outlined above, there will always be tasks which must be carried out in real flight. Actual flight at low level is currently the only way aircrew can experience the full cueing environment of the real world, especially the physical and visual effects of high-g manoeuvres (which no simulator, not even a centrifuge, can reproduce adequately). Aircrew must also be confident in what they do: real flight experience is essential in all areas of the flight envelope to enable them to build and confirm this confidence, and also to provide them with an opportunity to evaluate (and feel confident in) how simulation can be most useful in mission training. Nevertheless, simulation provides the necessary preliminary 'building block' to

develop this confidence in a safe and controlled environment.

The application of new technology alone does not guarantee training effectiveness and hence improved operational performance. Effective training transfer can only be achieved through careful consideration of the human factors issues (discussed in chapter 6), particularly through an overall systems approach to training.

A well designed training programme will be structured using both simulator and aircraft. It must be appreciated that to maximise training effectiveness, the simulator should not simply emulate the aircraft but rather it should be used as a training device which exploits its inherent advantages and mitigates its disadvantages.

Effective training includes support of the user organization, such as on-line control and evaluation of ongoing training on the basis of the overall training concept. These activities ensure that desired attitude, behaviour, and knowledge are acquired. It is not always recognised, however, that the success and value of simulation training depends heavily on the instructor. Successful training analysis recognizes the constraints of the user organisation. It would be fair to assume that each user organisation is different and subject to different constraints.

Appropriate use in simulator sorties of mission planning, briefing and debriefing processes (as would be part of an operational mission) would encourage a positive attitude to simulator training as a contributor to operational readiness.

2.2 Low altitude flight is the most difficult phase of fast-jet operations to simulate

Low altitude high speed flight is the most difficult phase of fast-jet operations to simulate because the task depends on piloting skill to maintain control of the aircraft and to perform the mission task in a stressful and demanding environment. Successful simulation therefore relies heavily on accurate modelling of the vehicle's handling qualities and on provision of adequate piloting cues from motion and visual out-of-the-window scene simulation. Accurate modelling of the aircraft's handling characteristics and on-board systems is perhaps the most obvious requirement of a Mission Simulator. Unfortunately many older devices fall short of this basic characteristic and receive poor aircrew acceptance because the simulator does not behave like the aircraft. Even today, the achievement of acceptable handling is still a topic which merits continuing study. The pilot's visual and motion cueing environment is reviewed in chapter 4. Motion cues are important to the pilot in maintaining control and orientation, while visual cues are particularly important for judging height and speed at low altitude. Conclusions relating to motion cues are discussed further in this section and to visual scene simulation in later sections.

In general terms the need for motion cueing depends upon many factors which include the task the pilot is required to fly, the handling qualities of the simulated vehicle, and whether the pilot is required to achieve the same level of performance, with the same workload, by employing a similar control strategy in the simulator to that employed in the real aircraft. Non-visual motion cues such as platform motion and G-seats are very important to the pilot because they provide cueing information the pilot cannot perceive visually. Motion cues derived from physiological sensors such as the vestibular organs do not require the pilot's attention and provide crucial feedback information necessary for the pilot to maintain control in a high gain closed loop control task such as low altitude high speed flight. Visual and non-visual motion cues are complementary and one source cannot be considered as a substitute for the other. In addition the application of properly harmonised non-visual motion cues can enhance the motion cues perceived by the pilot from the visual system, and also provide important stressors acting on the pilot.

2.3 Mission simulation - more complex than the aircraft itself

A Mission Simulator is a complex device, arguably more complex than the aircraft that it seeks to represent. This is because it must not only faithfully reproduce the performance of the aircraft, its weapons and systems but also adequately model and represent the external natural and mission environments within which the aircraft must operate during a simulated mission. The essential components of a mission simulator are described in chapter 3. The review of the task content of operational missions in chapter 2 reveals the wide variety of mission task events which make up typical missions, and which a mission simulator must be capable of simulating. The intent is to immerse the aircrew in a representative environment, with as many real world-like interactions as possible, in order to elicit the behaviour and strategies the aircrew would pursue in the operational situation. To support these representations requires the creation and maintenance of various databases (discussed in chapter 5).

The inclusion of aircraft avionics and mission systems in simulators is becoming increasingly complex. Including aircraft hardware in a simulator is expensive, but so is the work involved in simulating avionic and mission systems, with the added difficulty of keeping simulator software concurrent with aircraft modification. Some of the issues are discussed in chapter 7.

Provided source data for the relevant battle area is available, then it is possible to provide a realistic portrayal of the battle environment, in terms of its physical properties. Populating the battle environment with appropriate combatants (both friendly and hostile) can be achieved within the scope of a single simulator, provided the tactical behaviour of friendly and opposition forces can be realistically modelled. This is not yet entirely the case, and is a subject for continued research. It may be better for combatant elements in the battle environment to be provided via a network. This then facilitates the option of combatants being either computer-generated or provided by other human-in-the-loop systems.

There is a significant trend towards the networking of training devices, using both local area networks and wide area networks. This can provide a significant multiplier to the capability of a single machine as it can provide man-in-the-loop interaction with many players, or indeed can enable computer-generated forces to be shared among many simulators. There is a set of emerging standards for networking called Distributed Interactive Simulation. Trials have demonstrated the feasibility of both local and long haul networks using such standards, but much research and development is still required. Many issues remain to be solved, including the provision of a network infrastructure of adequate bandwidth, scenario definition and generation, and management and control of the whole simulation exercise.

Simulation has the potential to improve crew performance significantly in the execution of low level operations. By its very nature, it offers aircrew the opportunity to practice and perfect, in selected and controlled situations, the procedures which are necessary to ensure safe and mission-effective operations and which are difficult or very costly to achieve in the aircraft.

2.4 Simulation of the outside world visual scene

Simulation of the outside world visual scene, both visually and to represent sensors, is the critical technology in low level mission simulation. A complete visual system is a combination of three components: the image generator hardware; the scene database; and the display system. All three have weaknesses which need research to achieve better simulation of low altitude, high speed flight for mission training and rehearsal.

Visual scene simulation (discussed in detail in chapters 4 and 5) involves the generation of an image in a computer-based image generator (IG) and the display of that image using some form of display. Mission Simulation places significant demands on the visual system in order to provide a visual cueing environment which maximises the transfer of training benefit to the crew of the simulator. In the real world the visual image seen by the aircrew is characterised by a field of view limited only by the simulated aircraft structure; by unlimited image detail and very high scene content; and by brightness levels ranging from night to full daylight under bright sunshine.

Producing a synthetic visual system which provides such performance characteristics in a simulator is beyond the current and foreseeable state of the art in visual system technology. Fortunately, such performance is not necessary to achieve effective training, as compromises can be made. The performance required is a function of the mission task to be trained. The challenge for the Mission Simulator developer is to maximize the cueing benefit and transfer of training possible with the available technology. This still needs research. Some appropriate research is being conducted under the EUCLID programme, Research and Technology Projects RTP 11.1 and 11.2, which are expected to report by 1997.

2.4.1 Image generator capability

An image generator (IG) is essentially an advanced graphics computer, usually with a specialised hardware architecture, designed to perform the complex processes of generating a two-dimensional representation of a three-dimensional world, in colour with surface textures and numerous special effects - such as fog, smoke, dusk - all at high speed, 50-60 times per second or faster. The processing performance of the IG is usually the limiting factor in scene generation, in terms of the number of fully textured polygons that can be rendered at the desired rate.

Image generators are becoming available capable of generating the terrain and three dimensional features required for low level flight. It is now probable that the latest generation of high-end image generators, with photo-texture and more three dimensional objects,

coupled with an area of interest display system can provide sufficient scene content to enable manual high speed flight to be accurately maintained at low level over undulating terrain.

Simulators to be procured in the next 5 years are expected to employ advances such as photo-texture, higher resolution and more polygons producing more scene detail to support low-level high speed flying. Full colour photo-texture was not available in the Tornado test-bed or Harrier GR5 simulators. Such phototexture can give the appearance of improved modelling fidelity and potentially reduce the number of polygons required. But the effectiveness of photo-texture in simulated flight at 250 ft and below has yet to be demonstrated and needs research. The need to use truly three-dimensional terrain may still be required to provide such capability as visual occulting and terrain masking, the risk of collision and to supply height data for such sensors as terrain following radar.

From the point of view of the needs of full mission simulation, image generator systems can usually support only a relatively small number of moving vehicles simultaneously active in the instantaneous visual field of view. Typically this is restricted to sixteen to thirty-two targets, and may not rise above one hundred for some time without special development effort. This will become more important as the use of distributed interactive simulation, and the number of participants, grows.

Visual systems today fall short of being able to simulate the most demanding weather conditions. Current visual systems technology does not provide for accurate simulation of three-dimensional variations in density of cloud and, in particular, fog structures. Atmospheric mathematical models that exist today are inadequate for many conditions experienced in operations. New mathematical models need to be devised that are suitable for real-time simulation.

2.4.2 Scene Database

The scene database contains all the geometric data and other information needed to create a representation of the terrain, the features on the surface and the other vehicles and objects visible in the simulated world.

Key questions related to the scene database are how to define precisely what is needed in the visual scene to meet defined training tasks; how to acquire the appropriate real world data in sufficient detail for all areas of the world.; and how to reduce the time and cost of the process of transforming data to create the run-time database. All these questions need further research.

A highly detailed visual scene is necessary to support flight at low level to provide height, airspeed and navigation cues to the aircrew. The German Tornado programme has indicated that the scene should contain significant numbers of truly three-dimensional objects, such as trees, buildings, etc., as well as high frequency texture information and well defined terrain contours. These requirements imply image generation systems capable of providing at least 6-10 000 faces or polygons per channel as well as full colour textures.

Even then, undulating and mountainous terrain will still have to be portrayed in simplified form. Given the availability of terrain elevation data at grid spacings of 30 metre (level-2 DTED), the ability to render all such data into a set of polygons would require an Image Generator to process around 1 Million polygons per channel for a 25 mile visual range. This is two orders of magnitude greater than current systems and is not likely to be attained in the foreseeable future.

Techniques do now exist that allow databases to be optimised to match the performance of the image generator and display system for the mission. For real-time optimisation, scene management software controls the displayed scene to avoid overloading the image generator. By identifying the key cues for a mission, it is possible to design the database to suit the mission to ensure that mission-critical or other important objects are not removed from display by the scene management process.

The simulation of radar images is adequate and is likely to remain so in the foreseeable future. Adequate representation is more a database issue than one of display.

The simulation of Forward Looking Infra Red (FLIR) does not currently recognise the way that the thermal radiation of all objects and terrain should dynamically interact with each other over time. The complexity of such modelling is believed to be beyond the state-of-the-art capability for real-time simulation, even over the next five to ten years.

Producing large databases for mission simulation is expensive. The time to generate a database for a new area is a major concern, particularly where it is required for mission rehearsal. Collecting data for an appropriate geographical area of the world still requires

considerable effort and could be the limiting factor in rapid database generation for mission training and rehearsal. A major initiative for time and cost reduction has been the US DoD Project 2851. This project has now successfully established a source data interchange format, MIL-STD-1821. By adopting this US military standard for the interchange of source data, it should be possible to re-use selected source data when constructing new databases for the same geographical area. Terrain data derived from stereo-pair satellite images will become an increasingly important data source. Such data sources, combined with improved IG capabilities, should enable terrain to be portrayed to sufficient resolution to satisfy low-level flying requirements over most terrain types.

For mission rehearsal in a real battle situation, aircrew priorities are such that they will accept a lower standard of database than would be acceptable in peace-time training. Thus, while it may be possible to produce a useable database for a real-life mission rehearsal within forty-eight hours, it is considered unrealistic to expect that a large database of the quality that has become expected of training simulators will be produced that quickly. However, the use of standards and tools developed to support a rapid reaction capability will greatly improve on the current productivity for databases.

Correlation of databases is an issue that arises in single simulators with scene sensor devices such as radar or FLIR as well as out-of-the-window scene simulation. Using a common data source eases the problems of correlation across sensors for a single simulator. Achieving correlation across a number of different simulators which are networked is a bigger problem. If two simulators are to be linked, for example to provide a wing-man, the problem is less severe than in a fully distributed situation. It should be possible to obtain satisfactory correlation in such an application, particularly if both are specified and procured with this application in mind.

2.4.3 Visual Display System

The display system defines the visual field of view and resolution. Evaluation of current technology suggests that 'area of interest' systems, as used in the Harrier and Tornado simulators, will provide the 'best' solution in the medium term for the simulation of low level flight.

For ground attack and low level flight training, the visual display must present a highly detailed representation of the terrain contours and the features which are expected to populate it, with a field of view covering the forward area from the aircraft. The minimum total field of view required in a simulator is up to 180 degrees horizontally, and -60 to +90 degrees vertically, with limitations only due to aircraft structure, with a minimum instantaneous field of view of 120 degrees horizontally by 60 degrees vertically. The display resolution must be sufficient for the pilot to recognise cues and react to them while they are at relatively long ranges (the higher the airspeed the greater the range at which recognition is necessary) over the full field of view. At present, eye-limiting resolution can only be achieved with dedicated, small field-of-view target projectors.

Field of view and image resolution are fundamentally interrelated and, indeed, in conflict. The perceived resolution of a given number of image generator pixels is dependant upon the field of view over which they are displayed and the efficiency of the display system. The larger the field-of-view, the lower is the image resolution achievable for a given number of pixels. Conversely, the larger the field-of-view, the larger is the number of pixels needed to maintain a given resolution.

Some important aspects of visual displays, however, are subject to the realities of physics and are unlikely to improve. These include display brightness in domes, display resolution and contrast ratio.

The core technologies from which the simulation industry draws key elements, such as micro-electronics, fibre optics and display systems, are advancing rapidly, driven by consumer demands, particularly in the area of entertainment systems. These advances are expected to result in improvements in simulation systems in terms of higher performance image generators and higher performance display systems.

2.5 Procurement issues concerned with the provision of aircraft and systems data

There are important procurement issues which need to be addressed, particularly concerned with the provision of aircraft and systems data. This is discussed in detail in chapter 5.

Mathematical models of own-ship aircraft performance in current use are of adequate fidelity. The key issue is obtaining the data to produce valid implementations of specific aircraft. In general, data packages for military aircraft are inadequate. One way to improve this would be to ensure that the provision of data receives the attention it deserves at the contract stage during

procurement of the aircraft.

Where data are available, good fidelity modelling of the own-ship is possible to achieve the low altitude high speed mission requirements. Where such data are not available, the simulator performance, particularly at the envelope limits, must be validated to ensure a positive transfer of training. Correct modelling of the extremes of the envelope is especially important as pilots tend to use more envelope extremes in the simulator than in the actual aircraft.

Surprisingly, the definition of comprehensive data packages which provide the Mission Simulator developer with the data necessary to support the modelling of a combat aircraft is not a well-defined process. A data package definition has been in existence for some time in the commercial airliner simulation world, where aviation certification authorities such as the FAA and others control simulation standards by strictly relating the training credits that can be achieved on a simulator to the fidelity of the modelling. There is very close liaison between international authorities and hence the standards employed are essentially common throughout the industry. Military authorities have yet to establish such a unified approach. This would be a worthy subject for an AGARD working group.

2.6 Procurement issues concerned with decisions on the visual system to be employed

Many simulators may specify the best available visual system at the time of procurement but, by the time the simulator is in service, do not have visual systems that represent current state-of-the-art performance. This is because the procurement time for the development, build, integrate and test cycle for a complex simulator has been greater than the time between successive generations of image generators. This needs to be recognised in the procurement process, by deferring a decision on the specific image generator until as late as possible.

3 FINAL REMARKS

The level of realism attained in a particular simulator generally matches the funds available but political directives and training philosophy may drive the budget. A comparison of budgetary and political cost of such simulation versus full-up exercises may create a climate for broader acceptance of simulation.

This report has identified areas of work which could benefit from continuing multi-national study. The AGARD Flight Vehicle Integration Panel, as AGARD's centre of expertise in flight simulation, will pursue these ideas. Some examples are proposed in the recommendations that follow in the final chapter.

CHAPTER 9

RECOMMENDATIONS

CONTENTS

1 INTRODUCTION

This chapter offers some recommendations for further research required, as identified in the body of the report, in order to ensure that effective mission training and rehearsal simulators can be procured and deployed in the future.

Funding for simulation research is changing as a result of Government policy towards defence procurement. Historically, specifications for military full mission simulators stretched the technology of the day in an attempt to force the pace of innovation and development. Today, however, general reductions in defence expenditure, coupled with a drive towards greater cost effectiveness, have led many Governments to the procurement of commercial off the shelf (COTS) products using proven technology. This trend may constrain the rate of future progress. Fortunately, it seems likely that developments in other markets may stimulate some of the technical advances required by, and reduce the cost to, the defence community.

In particular, developments in the computing and entertainments industries will have an impact on the simulation industry. If the military are to exploit these developments for their own purposes, research will still be required to ensure that techniques and products are usable and have the required fidelity. A possible route to achieving defence-specific improvements is via international collaboration or national technical demonstrator programmes (TDPs), of which the German Tornado Low Level Test Bed Simulator (VTS) was an example.

In addition to technology-based research, there is also a need for research on how best to apply the technology available to achieve maximum training effectiveness. This research will rely on a greater understanding of the underlying fundamental science of human perception and psychology.

The remainder of this chapter identifies the key research needs and priorities.

2 RESEARCH NEEDS

2.1 Research Priorities

Research is required in many areas, including:

- visual scene generation and scene content
- visual scene display technology
- requirements and standards for scene database preparation
- natural environment models
- data package requirements and standards for aircraft and systems performance
- scenario generation methods and tools, the modelling of 'intelligent' forces, and data standards
- facilities for the instructor and for mission management
- motion cueing

- application of distributed simulation technology

These themes are elaborated further in the following sections.

2.2 Visual scene content

The highest priority is for research to define precisely what scene content is required to provide the cues to meet training needs and how to specify such scene content.

It has been established by the Tornado evaluation that a large number of three-dimensional objects are needed to provide height cues for simulated low-level flight. Research trials should be carried out to establish criteria for three-dimensional scene detail to suit specific training objectives. This should include studies to investigate the value of modern photo-texture technology in providing realistic scenes at low altitude, to determine whether photo-texture can substitute for increased numbers of polygons and to quantify the trade-off between the use of photo-texture and the demand for more polygon processing capacity. These studies should also assess the training effectiveness of such scene content.

Research is needed to ensure that image generators continue to improve their capacity to meet military requirements. For low level, high speed mission simulation, the following specific improvements have been identified to meet operational needs:

scene management - emerging techniques in artificial intelligence and fuzzy logic should enable the polygon/texture capabilities of the image generator to be utilised in the most efficient manner to ensure the best possible scene is presented at any given instant for the task in hand;

processing capabilities - to increase the polygon processing capacity, to simulate specular reflections and to provide a greater number of dynamic targets in the visual scene;

texture rendition - the appearance of texture at low grazing angles and at close viewing distances needs to be improved to provide realistic representations and to maintain sufficient detail to provide accurate height and speed cues.

2.3 Visual scene display technology

Area of interest display solutions offer the best available technology for the present and the medium term to satisfy the need to provide low level flight training in a synthetic training device. Research is required on the role of foveal versus peripheral vision and the contribution each makes to the overall perception of the scene. The information gathered would allow better specification of the image generator performance requirements for the background and inset channels of such display solutions.

In currently fielded aircraft, the head-up display provides the aircrew with the principal reference with which visual system accuracy and correlation with other sensors can be judged. The visual system accuracy and distortion characteristics must, therefore, be optimized in the area covered by the aircraft head-up display, in order that the visual target will correlate properly with the tracking data presented on that display. Future weapons and sensor technology, with off-axis aiming of weapons and possibly incorporating helmet-mounted sighting systems, will challenge the ability of simulators to provide an adequate simulation. In particular, these developments will extend the display accuracy requirements to cover the whole field of view. Research is therefore required to ensure that image generators and display systems, in combination, are capable of meeting these accuracy requirements.

Research is required on visual presentation methods to provide the necessary field of view together with increased resolution, non-interlaced displays, and higher frame rates.

2.4 Requirements and standards for scene database preparation

Collecting data for a specific geographic area still requires considerable effort. For some parts of the world, data is not readily available. There is a need for continuing research and development on workstation-based software tools for database generation, maintenance and management. Research is also required on how to exploit new data sources, to interchange and re-use databases and to enable users speedily to produce new databases and subsequently to modify and update them during the life-time of a simulator. This should include study of the requirements and standards for scene database preparation, including methods and tools to handle and process satellite images and other photographic sources, from which to generate terrain profile and feature data. Research on these tools should

include methods to deal with image processing issues such as ensuring consistency in colour balance, and coping with differences due to time of day and season of the year.

Research on improved modelling of Forward Looking Infra Red (FLIR) images, particularly to include dynamic interactions between objects and the surrounding terrain should be undertaken, but may need to be a long-term project.

To reduce the cost of producing visual databases, future simulator procurement specifications could usefully include a requirement something like the following:

> "Visual databases shall be supplied in the SIF/HDI source data interchange format, MIL-STD-1821. By adopting this US military standard for the interchange of source data, it shall be possible to re-use selected source data when constructing new databases. Any database generation facility shall have the ability to import and export databases in SIF/HDI format."

2.5 Natural environment models

Modelling of demanding weather conditions is limited by both visual system technology and the lack of adequate atmospheric models and data. No great improvement in this situation will occur unless specific research is conducted in this area, to produce advanced mathematical models suitable for real-time use to give improved 3-D modelling of weather and visibility.

2.6 Data package requirements and standards for aircraft and systems performance

A key issue is obtaining the aerodynamic and system data to produce a valid implementation of a specific aircraft. In general, data packages for military aircraft are inadequate. One way to improve this would be to ensure that the provision of data receives the attention it deserves at the contract stage during procurement of the aircraft. Further technical study of how best to achieve accurate simulation of an aircraft's handling characteristics, including cue harmonisation is recommended, the aim being to boost aircrew acceptance of mission simulators.

A military equivalent of the IATA document *'Flight simulator design and performance data requirements'*, (IATA, 1993), to provide a definition of data package requirements for military simulators, should be produced. Such work would be an ideal candidate for multi-national collaboration under AGARD leadership.

There is a need to encourage processor and interface standards for avionic systems across manufacturers and aircraft. A military equivalent of ARINC 610 should be produced for military simulation.

2.7 Scenario generation methods and tools, the modelling of 'intelligent' forces, and standards

The behaviour of friendly and opposition forces, as embodied in computer-based representations, needs to be realistically modelled. Emerging techniques in artificial intelligence should be explored to provide intelligent behaviour to players within an interactive scenario.

Provision of sufficient and adequate validated data to describe enemy threats and targets is one of the principal challenges in generating a mission environment. There are, as yet, no standards for the definition and exchange of such data between different tools. Work should be undertaken to define such standards.

2.8 Facilities for the instructor and for mission management

Facilities for the instructor and for mission management need to be improved. Research is required on the human-machine interface at the instructor station and on methods to display information to the instructor for such activities as briefing and scenario management.

2.9 Motion cueing

Results from the Tornado simulator test-bed support the use of platform motion for low altitude, high speed flying. For other mission tasks, such as air-to-air combat, more research is required to define what motion cues are needed for what tasks and how they should be provided. US and European views on the role and value of motion cueing in training simulators differ; further research should be undertaken on this. The trend to deployable training devices also needs research on compact forms of motion cueing device other than motion platforms.

The relationship between the use of modern motion cueing systems and training effectiveness is not well established. A review of research literature into the influence of platform motion on the transfer of training for fast-jet pilot training revealed no modern research

on this topic. Further research is therefore recommended.

2.10 Application of Distributed Interactive Simulation

Research is needed on the application of distributed interactive simulation (DIS) technology to aircraft training simulators, including assessment of acceptable latency, the provision of a network infrastructure of adequate bandwidth, scenario definition and generation, and management and control of the whole simulation exercise.

The value of networked players versus a computer-driven wing-man or opponent needs to be studied.

Studies of the value of an independent inter-visibility environment server should be undertaken, for use with distributed interactive simulations.

Correlation of databases is a challenging issue. Correlation across sensors on a particular simulator is much easier than achieving correlation across a number of different networked simulators. Methods to achieve correlation in both contexts merit further study.

3 ROLE FOR AGARD

3.1 Research coordination

There is a continuing role for AGARD to stimulate and coordinate research on piloted flight simulation technology. Despite the substantial sums of money invested in buying military training simulators, and the increasingly key role that simulators play in achieving operational readiness and effectiveness, research on piloted flight simulation technology and training effectiveness is neither well-funded nor widespread. Organisations which conduct such research include

Canada:	University of Toronto
Germany:	Forschungsinstitut für Anthropotechnik Wachtberg (Research Institute for Human Engineering)
	Universität der Bundeswehr Munchen, Fakultät für Luft- und Raumfahrttechnik
	Zentrum fur Flugsimulation Berlin (ZFB)
Netherlands:	National Aerospace Laboratory, NLR, Amsterdam
	Technical University, Delft
UK:	Defence Research Agency, Bedford and Farnborough
USA:	Armstrong Labs, USAF
	Army Research Institute, Fort Rucker, Alabama
	Institute for Simulation and Training, University of Central Florida
	NASA Ames, California
	NAWC-TSD Orlando, Florida

It is recommended that the Flight Vehicle Integration Panel continue to foster collaboration and coordination of simulation-related research among these organisations.

3.2 Future AGARD Working Groups

This report has identified several items which might form the subject for future AGARD Working Groups. These are:

- The NATO nations may wish to explore how a common store of reference source data for visual and sensor scene databases, to MIL-STD-1821 standards, may be established.

- It would be useful to define the content of a comprehensive data package for military flight simulators, based on the existing IATA document used in civil aviation.

- It would be useful if Military authorities were to establish a unified approach to simulation standards by strictly relating the training credits that can be achieved on a simulator to the fidelity of the modelling, as is done in civil aviation.

- Networked simulators have not been examined in detail in this report. This is a subject that needs further work. This would be a good theme for AGARD, to explore multi-national interests and the needs of Allies.

- There is a need to define standards across all aspects of simulation to improve re-use and hence reduce costs.

CHAPTER 10

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14. Abstract

This report presents the result of work by Working Group 20, established by the AGARD Flight Mechanics Panel to examine the current capability and future potential of simulation technology in low altitude, high speed, mission training and rehearsal.

The report contains much general information about mission tasks, mission simulation and simulation technology which it is hoped will be of interest to many people involved in the acquisition and exploitation of piloted flight simulators. The content is deliberately not limited merely to the specific cueing issues of simulating high speed flight close to the ground. The report deals primarily with fast jet aircraft but many technical factors are common to rotary wing vehicles.

Key conclusions include:
— training simulators and the aircraft must be viewed as complementary components in the total training package;
— full mission simulation is a complex task, and low altitude flight is the most difficult phase of fast-jet operations to simulate in terms of the cues needed by the pilot;
— simulation of the outside world visual scene, both visually and to represent sensors, is the critical technology;
— there are important procurement issues which need to be addressed, particularly concerned with the provision of aircraft and systems data, and with decisions on the visual system to be employed.

Recommendations for further research include the following topics:
— visual scene generation and scene content;
— visual scene display technology;
— requirements and standards for scene database preparation;
— natural environment models;
— data package requirements and standards for aircraft and systems performance;
— scenario generation methods and tools, the modelling of 'intelligent' forces, and data standards;
— facilities for the instructor and for mission management;
— motion cueing;
— application of distributed simulation technology.

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